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Environmental sustainability of phosphorus recycling from wastewater, manure and solid wastes

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Abstract

Phosphorus (P) is an important critical material essential for crops cultivation and animal husbandry. Effective phosphorous recycling is considered one of the most significant factors in alleviating its criticality. However, despite the importance of phosphorous recycling, its sustainability is not studied extensively. This paper aims to answer the question if recycling of phosphorus is an environmentally sustainable option. To address this problem, two issues are analyzed in this paper: energy consumption and greenhouse gas (GHG) emissions in phosphorous recycling. The analysis was performed by simulating mass and energy flows in the global phosphorus supply chain (from mining to recycling) in order to understand and analyze its environmental impact in 2000-2050. The results of simulation show that around 82% of recycled phosphorous originates from manure. Moreover, the calculations indicate that about 70% of total GHG emissions from phosphorous recycling is caused by wastewater processing. In addition, the results show that phosphorous obtained from recycled wastewater constitutes only 2% of the whole amount recovered in the recycling process. Therefore, the obtained results show a clear need for a detailed analysis of the sustainability of phosphorous recycling processes. Moreover, the analysis of scenarios of phosphorus consumption indicates that GHG emissions increase slowly in the mining phase and grow exponentially in the recycling stage. The main finding of this paper contradicts the general opinion about environmental friendliness of recycling. It shows that phosphorus recycling is not a sustainable solution in a longer perspective.

Keywords: Critical materials; phosphorus; energy consumption; greenhouse gas emissions; recycling; dynamic modeling

1. Introduction

Supply of phosphorus (P) and its current consumption pattern is not sustainable in a long term (Childers et al., 2011; Daneshgar et al., 2018b). The major areas of concern associated with sustainability of phosphorus were its scarcity (George et al., 2016), need for recycling (Morse et al., 1998), environmental pollution (Daneshgar et al., 2018a) and call for new sustainable policies and strategic framework (Cordell et al., 2011). Therefore, recycling or recovery of phosphorus from waste streams has been proposed as a possible approach to handle the issue of its sustainable use (EU Commission, 2017; Withers et al., 2015b, 2015a).

The initial concept of criticality originates from the concerns about the availability of raw materials. The general understanding of the criticality of resources is based on their scarcity and high demand (Calvo et al., 2018; Frenzel et al., 2017). It is commonly acknowledged that the criticality of materials is determined by several aspects such as supply risk, economic importance and vulnerability to supply restriction (El Wali et al., 2018; Rahimpour Golroudbary et al., 2019). However, we lack a generally accepted definition of critical materials due to the differences in methodologies applied for criticality assessment (Frenzel et al., 2017; Jin et al., 2016).

Phosphorus (P) has been identified as an important critical material according to many assessments (EU Commission, 2017; Ober, 2018; Scholz and Wellmer, 2013). Phosphorus is a chemical element which is primarily obtained from the phosphate rock. Sustainable supply of this element is essential for plants and animals, in particular for the security of food supply (Diallo et al., 2015). For over half a century, phosphorus has been one of the non-substitutable resources in food production (Jacobs et al., 2017) and about 50% of food production is based on the use of mineral phosphate rock (Scholz and Wellmer, 2013, 2015a).

The amount of mined phosphate rock ore depends on several factors, e.g. technological developments, exploration efforts, demand, price level (Scholz and Wellmer, 2013). A limited number of countries - Morocco and Western Sahara, China, Algeria, Syria, Russia, and South Africa - control 88% of the world phosphate rock reserves (Chen and Graedel, 2016). Globally, more than 90% of the anthropogenic input to the phosphorus life cycle is used for agro-food production including animal feed. The rest is applied as food and feed additives as well as other industrial phosphates (Scholz and Wellmer, 2015a). There is no danger of imminent shortages of phosphorus despite its limited resources (Scholz and Wellmer, 2015b). However, due to the already mentioned significant role of phosphorus in the global food chain, its global scarcity may have huge impact on the future food security (Cordell and Neset, 2014). In 2015, the global production of phosphate rock increased due to strong growth in global phosphorus consumption (Scholz and Wellmer, 2015a) and most of it was reported in the Middle East and South America (Ober, 2018).

Phosphorus is not only a case of particular concern in terms of resource management, but its mining could also be potentially disturbing to the environment (Rowe et al., 2016; Scholz and Wellmer, 2016). The policy measures adopted within the framework of the circular economy (increased recycling rates and waste reduction of critical raw materials) should mitigate not only future potential supply risks of these materials, but also the environmental impact associated with their life cycle (Elia et al., 2017; EU Commission, 2015). From this perspective, there is a global trend towards improved recovery of phosphorus. It has been demonstrated that a global co-operation for recycling and reuse of phosphorus in waste streams is urgently required (Dawson and Hilton, 2011; Elser and Bennett, 2011). Therefore, recycling of phosphorus needs to be considered as an integral part of phosphorus management policies. Otherwise, considerable fraction of phosphorus existing in the waste streams will be permanently lost.

On the other hand, environmental performance at each stage, e.g. mining, processing and production or recycling is one of the important criteria in the assessment of overall sustainability of phosphorus supply chain. The impact of energy consumption on the sustainability of a supply chain is well-known (Azadeh and Arani, 2016). It is manifested by the depletion of non-renewable energy resources and greenhouse gas (GHG) emissions. It is worth to mention that the rapid growth of agricultural production has major impact on development of mining and recycling of phosphorus (Wu et al., 2017). The scale of the phosphorus supply chain motivates the attempts to assess its environmental impact. One of its elements is the analysis of phosphorus supply chain aimed at quantitative assessment of energy consumption and GHG emissions.

In recent years, several studies have offered a quantitative analysis of phosphorus flow. Some of them introduced structural models at various scales, e.g. regional (Chowdhury et al., 2016; Theobald et al., 2016), national (Cooper & Carliell-Marquet, 2013; Li et al., 2015), continental (Jedelhauser and Binder, 2015; Matsubae and Webeck, 2019; Ott and Rechberger, 2012), and global (Chen & Graedel, 2016; Y. Liu et al., 2008; Van Vuuren et al., 2010). In this paper, we introduce a dynamic model to analyze environmental impact of phosphorus supply chain at global scale.

The main objective of this study is to answer the question whether recycling of phosphorus is an environmentally sustainable option viable in a longer perspective.

2. Model of Phosphorus Global Supply Chain

The need for a systematic analysis of phosphorus supply chain has been presented in different studies, e.g. Chen and Graedel (2016); Kleinman et al. (2015); Cordell (2013); Neset et al. (2016); and Van Vuuren et al. (2010). This paper aims at determining energy consumption and GHG emission at different stages of phosphorus supply chain using the system dynamics modeling (Forrester, 1997). The analysis presented in this paper covers a 50-year time horizon. The reason for this time interval analysis is a need to explore future global environmental impact of phosphorus mining, processing and recycling. Also, we consider significant challenges of phosphorus supply in the near future. For example, it is predicted that we will face 50-100% increase of phosphorus demand in 2050 (Cordell et al., 2009; EFMA, 2000; Steen, 1998). It will be triggered by the growth of global demand for food (up to 70% by 2050) and a changing diet (e.g. growing interest in meat and dairy-rich diet, which requires phosphorus intensive food production) (Fraiture, 2007). In the case of phosphorus, several approaches have been applied to analyze dynamic interactions among various components of the system under investigation, e.g. phosphorus mass flow (Modin-Edman et al., 2007), solid waste management (Kollikkathara et al., 2010), decoupled aquaponics system (Goddek et al., 2016), phosphorus flows in food and waste chains (Treadwell et al., 2018), and the impact of recycling improvement on phosphorus life cycle (El Wali et al., 2018).

Figure 1 gives an overview of the proposed model. The system consists of three sub-systems: material flow, energy consumption and GHG emission. The material flow sub-system is composed of the following modules: mining, beneficiation, processing, production, consumption, waste generation, and recycling. The energy consumption sub-system includes energy consumed in mining, processing and production as well as recycling. The GHG emission sub-system is primarily related to the energy consumption and therefore the structure of both subsystems is identical. The details of the structure of a dynamic model are given in Appendix (Figures A1 and A2) as well as notation and the used data are presented in Appendix (Tables A1 and A2). Figure A1 (a) represents the mass flow across the different stages of phosphorus supply chain starting from mining and ending at the post-consumption stages. Figure A1 (b) shows mass flow of phosphorus across the waste streams where material goes to recycling, loss, landfill or other applications. Figures A2 shows the relationship between energy consumption and

GHG emissions in mining stage of phosphorus supply chain, as an example. The sources of data, used as an input into the calculations of material flow, energy consumption and GHG emissions, are presented in Figure 2.

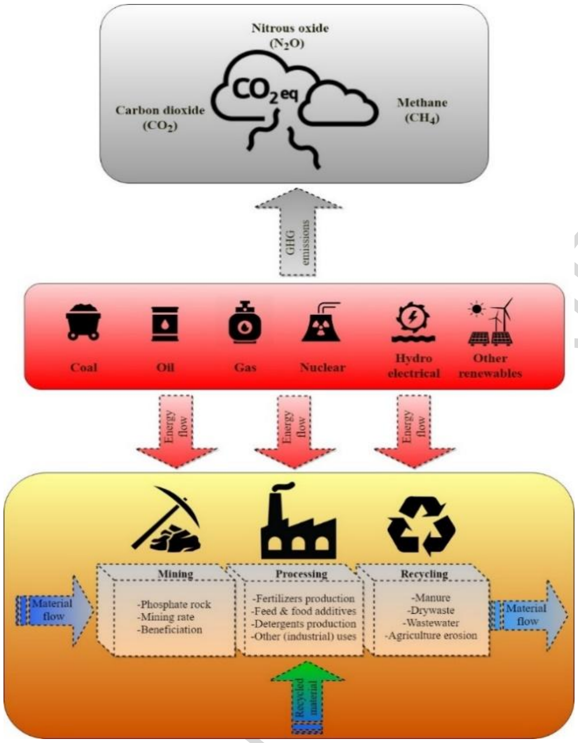

Figure 1. Conceptual model of phosphorus global supply chain.

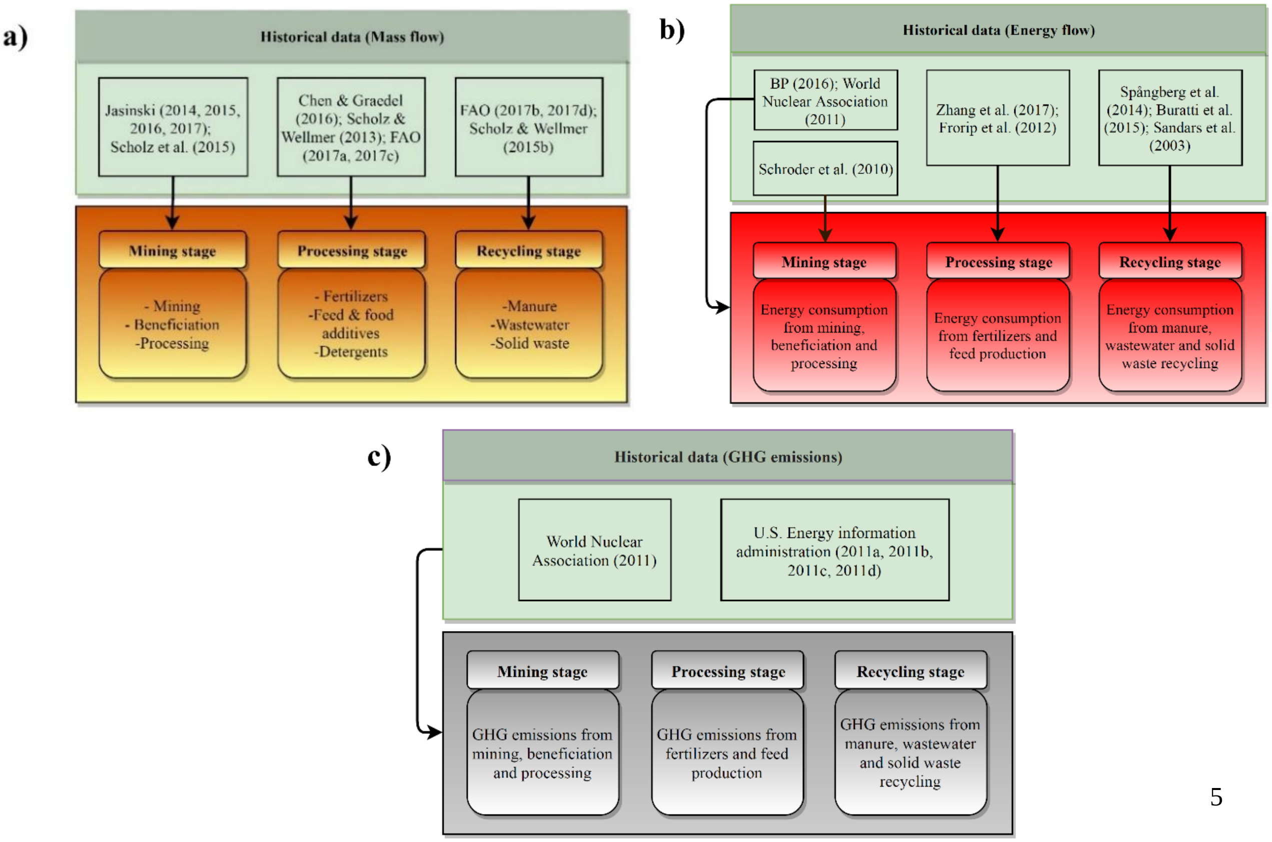

Figure 2. Data sources of three stages of the phosphorus supply chain. a) material flow; b) energy consumption; c) GHG emission.

2.1 Material flow of phosphorus model

We can distinguish three main steps in the phosphorus supply chain. The first step is the industrial stage, where phosphate ores are mined, and next processed applying the beneficiation process (Chen and Graedel, 2016; Koppelaar and Weikard, 2013; Scholz and Wellmer, 2015a). The second step corresponds to the production stage, where phosphorus is present in various streams, e.g. agricultural fertilizers, feed and food additives, laundry detergents and other industrial applications (Belboom et al., 2015; Mottet et al., 2017; Noya et al., 2017; Van Hoof et al., 2017). The final step corresponds to the dissipation and the recycling of phosphorus (Chen & Graedel, 2016; Fowdar et al., 2017; Harris et al., 2017; Hobbs et al., 2017; Leon & Kohyama, 2017; Maguire & Fulweiler, 2017; Ortiz-Reyes & Anex, 2018). In recycling, other materials such as nitrite associated with phosphorus can be recovered in parallel. However, the analysis of their flows is beyond the scope of this model.

Fertilizer industry is the major user of phosphoric acid (Belboom et al., 2015). Fertilization of soil, aiming at the increase of crop yield, is done thanks to phosphorus originating from fertilizers and recycling streams. In this work, the production of the following crops was considered: rice, wheat, barley, sorghum, millet, rye, oats, potatoes, sweet potatoes, cassava, soybeans, beans, peas, rapeseed, olive, sugar beet, sugar cane, seed cotton, vegetable, and fruits. The produced crops are used as feed and food (Mottet et al., 2017; Noya et al., 2017). The feed is consumed by the livestock. In the presented model, we considered the feeding of the following animals: sheep, goats, horses, cattle, buffaloes, mules, pigs, ducks, chickens, geese, and turkeys.

There are losses of phosphorus along its supply chain. Major amounts of phosphorus are released into the marine systems. It takes place in mining, beneficiation and processing of phosphorus (Chen and Graedel, 2016). In addition, a significant amount of phosphorus enters water resources through soil in the process of agricultural production. A substantial amount of phosphorus is removed from the soil through crops harvesting. The rest of phosphorus remains in the soil as a surplus and is retained in it. The loss of phosphorus occurs due to various phenomena; e.g. soil loss, leaching, runoff and erosion (Fowdar et al., 2017; Harris et al., 2017; Ortiz-Reyes and Anex, 2018). Another source of phosphorus in the marine system is the effluents containing detergents, industrial wastewater and animal production waste (Chen and Graedel, 2016; Hobbs et al., 2017; Maguire and Fulweiler, 2017).

Moreover, the human factor has twofold impact on the phosphorus loss to inland waters. First, the increasing population accelerates the leakage of phosphorus through land-water interface towards the coastal zones (Withers et al., 2014). The second factor is urbanization (Matsubae and Webeck, 2019).

Currently, recycling is considered as one of the best solutions to manage phosphorus management challenges. Recycling is the process of turning waste into usable materials. The recycling of phosphorus takes place mainly in agriculture. It is based on the use of various sources containing P, e.g. sludge from wastewater treatment (Shiu et al., 2017; Ye et al., 2017), livestock manure (Haase et al., 2017) and dry waste (Pearce and Chertow, 2017). Therefore, in this study, the main waste streams considered in the phosphorus supply chain are wastewater, manure and solid waste and, as a result, the recovery of phosphorus from those three streams is investigated.

The significance of phosphorous recovery from wastewater has been presented in many studies (Kumar and Pal, 2015; Musfique et al., 2015). They showed that wastewater treatment provides a good opportunity for phosphorous recovery. Recovering phosphorous from wastewater could considerably reduce eutrophication and create a supplementary source of fertilizers (Ye et al., 2017). The second main stream at the recycling stage corresponds to manure. According to the previous research, in Europe, manure contains around 2000 Kt/a of phosphorus, that is much higher than the amount of phosphorus in sewage and slaughter waste (Buckwell & Nadeu, 2016; Leip et al., 2014). As recycled manure goes directly to fields, most of phosphorus stays within agricultural applications. Manure considered in this study comes from donkeys, cattle, buffaloes, chickens, ducks, mules, sheep, goats, and pigs. In the third main recovery stream of phosphorus, the recycling of solid waste takes place in the composting process. An efficient management of solid waste is needed to limit and possibly decrease the environmental burden. Collected solid waste is immediately treated and next either recycled or used in other applications, e.g. landfilling (Behrooznia et al., 2018).

2.2 Energy consumption according to phosphorus model

During the mining of phosphate ores, energy consumption is mainly associated with the use of mining machines and equipment. That equipment includes draglines, pumps, pit cars, and equipment necessary for water treatment, pumping, beneficiation and transport of raw material to phosphate processing sites (Schroder et al., 2010).

In the production stage, the production of feed and fertilizers are analyzed separately. Energy demand in feed production varies between its different types. In this paper, the analyzed types of feed are hays, barley, maize (gluten meal, grains and silages), oats, salts and minerals, soybeans, and wheat. This study considers the direct energy inputs for feed production, which includes the energy used in feed processing and by the delivery machinery (Frorip et al., 2012). Energy demand for phosphate fertilizers production corresponds to the energy used by the slurry method (X. Zhang et al., 2017). The data for energy demand correspond to the production of two phosphate fertilizers (mono ammonium phosphates and di-ammonium phosphates). Those two types of fertilizers are the most commonly produced phosphate fertilizers in China.

In the recycling stage, our study is limited to the analysis of energy demand related to the recycling of phosphorus from waste streams coming from wastewater, food, animal, human excreta and households. In this work, the data presented by Sandars et al. (2003) are used as a basis for determining the energy requirements of manure recycling. The following sources of manure for recycling are analyzed here: animal origin, households, anaerobic digesters, storage lagoons, and land application of other residues.

The wet chemical approach and the thermo-chemical treatment are the two main technologies for P recovery from sludge produced from wastewater treatment plants (Appels et al., 2010). In wet chemical process, strong acids are added to extract P from the sludge phases. Thermo-chemical treatment refers to the addition of chloride additives to remove heavy metals from the sludge, thus facilitating the chemical removal of P (Ye et al., 2017). It is worth to mention that phosphorous recovery from wastewater is difficult due to different sludge compositions (Amann et al., 2018). The data given by Buratti et al. (2015) were used for determination of energy consumption in recycling of phosphorus from solid waste. There are mainly two treatment technologies of waste for P recovery, undifferentiated and source separated collections. In both cases, the treatment of waste and recovery of phosphorous is performed using aerobic biological facility. The undifferentiated collection is meant primarily for the landfilling of waste. In this paper, we consider the second option, source separated collection, in which treated waste is composted as fertilizers.

2.3 Greenhouse gas emissions according to phosphorus model

Carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4) are the major greenhouse gases (GHG) (Brander, 2012). The emissions of these gases occur in different processes either directly (e.g. during agricultural activities) or indirectly (e.g. during the process of mining, production and recycling) (Massé et al., 2011; Wood & Cowie, 2004). In this model, as mentioned above, the structure of GHG emissions sub-system is identical to the system of energy flow. Therefore, we analyzed the GHG emissions related to energy consumption in mining, production (e.g., fertilizer and feed), and recycling (e.g., manure, wastewater and dry waste).

The required data of the sub-model of GHG emissions originate from specialized reports (World Nuclear Association, 2011; US Energy Information Administration (2011a)), Figure 2(b-c). These data sources are used to estimate the share of each gaseous emission (CO_2, CH_4 or N_2O) and its sources (coal, nuclear, gas, oil, renewables).

2.4 Mathematical formulations

Dynamic modeling was used to simulate the phosphorus supply chain. The model was built using the concept presented in Figure 1. Below, we present the main formulas used in calculating material, energy, and GHG flows. All equations derived from the main formulas and the details of the model are given in Appendix, Tables A1-A3.

There are two types of equations in the model, which represent the flow of mass, energy and GHG: stock equations (state equations) and flow equations (rate equations).

The stocks assumed in the material flows of the model are: mined and beneficiated phosphorus, phosphoric acid, detergents, fertilizers, feedstock of vegetable and animal food, crops, food, livestock, food waste, animal waste, dry waste, wastewater stock, and organic fertilizers. The mass stock equations are given after Forrester (Forrester, 1997) as:

$$Stock(t) = \int_{t_0}^{t} [Inflow(t) - Outflow(t)]dt + Stock(t_0) \qquad (1)$$

where t_0 is the initial and t is the final year considered; $Stock(t)$ is a mass accumulated in the system in the moment t of the period *2000-2050* due to influx $Inflow(t)$ and loss $Outflow(t)$.

$$Inflow(t) = f(Stock(t), V(t), P);$$
$$Outflow(t) = f(Stock(t), V(t), P) \qquad (2)$$

where, $V(t)$ is an exogenous variable in time t, e.g. the beneficiating rate depends on the amount of extracted phosphorus and the stock of globally mined phosphorus every year. P is a parameter considered in the system, e.g. beneficiating coefficient, phosphorus content in P_2O_5 and P_2O_5 content of phosphate rock (All parameters are presented in Appendix, Table A2).

Every stage in the supply chain consumes energy obtainable from the different sources. The rate equation for energy is given as Equation (3).

$$EC_m(t) = P_m(t) \times \sum_{n=1}^{6} \sigma_{m,n} \qquad (3)$$

where, $EC_m(t)$ is energy consumption of stage m in the moment t of the period *2000-2050;* m= *1,2,3* represents stage of the phosphorus supply chain: mining, processing, and recycling; n= *1,2,...,6* corresponds to the type of energy obtainable from different energy sources: coal, nuclear, gas, oil, hydroelectricity and other renewables; $P_m(t)$ is the amount of phosphorus in stage m in the moment t of the period *2000-2050;* $\sigma_{m,n}$ is the energy required per one ton of phosphorus flow in a given stage m= *1,2,3* (mining, processing, and recycling) from each energy source n= *1,2,...,6* (coal, nuclear, gas, oil, hydroelectricity and other renewables).

The GHG emissions are estimated based on energy consumption in the phosphorus supply chain. The rate equation of GHG flows is formulated as:

$$GHG_{x,m}(t) = EC_m(t) \times \sum_{n=1}^{6} \delta_{x,n} \qquad (4)$$

where, $GHG_{x,m}(t)$ represents greenhouse gas emissions of type $x = 1, 2, 3$ (CO_2, CH_4 or N_2O) in m stage of the supply chain, m= *1,2,3* (mining, processing, and recycling) in the moment t of the period *2000-2050;* $EC_m(t)$ is the energy consumption in stage m= *1,2,3* (mining, processing, and recycling in the moment t of the period *2000-2050;* $\delta_{x,n}$ is the GHG emitted as type $x = 1, 2, 3$ (CO_2, CH_4 or N_2O) per one joule of energy consumed using the n resource, n= *1,2,...,6* (coal, nuclear, gas, oil, hydroelectricity and other renewables).

2.5 Validation of the model

Usually, in order to determine the validity of the model the obtained outputs are compared against experimental data and their statistical compliance is tested. The method proposed by Barlas (1996) was used for the validation of the proposed model. The variables such as fertilizer and feed production as well as manure recycling rates were used to validate the model. Differences between the results obtained from the model and experimental data of the above-mentioned variables on average amounted to 0.04, 1.44 and 1.90%, respectively. The results of validation and calculation of the error of the model are presented in Table 1.

Table 1. Calculation of the model error.

	Historical data			Simulation model results		
Year	Fertilizer production*	Feed production**	Manure recycling***	Fertilizer production	Feed production	Manure recycling
2000	N/A	1,301,851.60	13,304,913.32	-	1,452,755.5	14,126,384.05
2001	N/A	1,356,200.56	13,386,242.41	-	1,585,635.13	14,321,608.75
2002	16,087,280.14	1,347,503.36	13,540,544.05	20,196,138.11	1,414,358.00	14,111,058.49
2003	17,061,371.41	1,349,972.08	13,745,584.98	18,744,831.81	1,477,137.52	13,884,506.86

	Historical data			Simulation model results		
Year	Fertilizer production*	Feed production**	Manure recycling***	Fertilizer production	Feed production	Manure recycling
2004	17,986,839.42	1,457,628.76	13,985,807.53	18,709,318.15	1,417,280.63	14,114,006.80
2005	18,398,560.64	1,444,219.52	14,223,828.63	19,909,526.19	1,380,451.96	14,381,810,55
2006	18,107,386.42	1,424,900.04	14,434,801.65	22,554,161.72	1,378,671.73	13,980,106.01
2007	19,205,169.53	1,441,938.36	14,647,319.06	20,805,530.76	1,477,424.94	14,241,787.37
2008	20,150,567.45	1,557,968.28	14,774,087.36	20,067,328.42	1,347,941.07	14,403,686.46
2009	18,991,954.18	1,489,393.52	14,850,020.48	20,366,313.65	1,388,951.29	14,263,566.09
2010	21,752,206.61	1,515,894.32	14,884,771.53	18,438,580.86	1,451,976.45	13,976,649.00
2011	23,243,419.59	1,590,210.84	14,888,172.36	21,982,372.77	1,462,088.08	13,870,226.49
2012	22,944,776.89	1,582,593.92	15,038,770.34	20,096,501.86	1,353,806.82	14,172,936.77
2013	22,843,212.38	N/A	15,102,132.7	21,772,061.33	-	14,068,006.76
2014	23,270,725.43	N/A	15,260,869.27	16,295,006.91	-	14,041,772.72
Ave.	20,003,343.85	1,450,790.40	14,404,524.38	19,995,205.58	1,429,883.01	14,130,540.88
			Error	0.04 %	1.44 %	1.90 %

* Initial data based on FAOSTAT source are given in tons P_2O_5 (FAO, 2017a). Conversion factor to tons phosphorus assumes 0.436 (Scholz et al., 2014).

** Data based on FAOSTAT data source for the production of crops used as feed commodities (FAO, 2017b). P content in crops is taken from Chen and Graedel (2016).

*** Data based on FAOSTAT source showing the amount of manure applied to soil (FAO, 2017c). P content in manure is based on FAO report on the environmental impact of manure (FAO, 2017d).

3. Results and Discussion

Simulation results are given in Figure 3 (a-f). Energy consumption and emissions of GHG in mining, processing and recycling stages are illustrated in Figure 3 (a-b), Figure 3 (c-d), and Figure 3 (e-f) respectively.

In the mining stage, energy consumption fluctuates dynamically and CO_2 emission reaches the highest level as shown in Figure 3 (a-b). The main cause of the observed trend along the supply chain is the dynamics of phosphorus flow from mining to recycling. This phenomenon has been also observed by Chen and Graedel (2016). The trend of energy consumption and consequently GHG emissions in the mining stage is influenced by the continuous change in the market value of phosphate rock. Calculations in the mining stage show the annual mean of GHG emissions is estimated at around 70 million metric tons CO_2 equivalent (mt CO_2e) between 2000 and 2050.

The consumption of mined rock in different sectors has fluctuated significantly for the past 20 years. In the processing stage (Figure 3 (c-d)) energy consumption also fluctuates continuously. These changes produce different GHG emissions at this stage. In 2013, the level of GHG emissions reached about 197 mt CO_2e as a result of the decrease in energy consumption. This decrease reflects changes in material production in the phosphorus supply chain. Global demand for phosphate fertilizers decreased in 2013 from 41.6 to 40.3 mt P_2O_5 – equivalent to 17.6 mt phosphorus – from which it increased to 41.3 million mt P_2O_5 in the following year 2014. Changes in demand for fertilizers caused a decrease in the processing stage of phosphorus supply chain in 2013, which significantly affected energy consumption and GHG emissions. The maximum amount of GHG emissions was estimated at up to 237 mt CO_2e in 2034. In another study by Cordell et al. (2009), the global peak of phosphorus production was estimated around 2030. The model shows an increasing trend in GHG emissions from 2014 to 2015. This reflects the increase in mining production in 2015. According to Scholz and Wellmer (2015a), the increase in the global mining production in 2015 was due to the growth in global consumption of phosphorus. Calculation shows that the annual mean of GHG emissions from the processing stage is ca. 220 mt CO_2e in the given period (2000-2050).

Considering the recycling stage (Figure 3 (e-f)), Figure 3 (e) shows the impact of the reduction of phosphorus production on the supply of phosphorous to the recycling stage. For example, the collapse of the Soviet Union (FSU) between 1989 and 1993, resulted in dramatic decrease of fertilizer demand in processing stage. Moreover, demand for phosphate fertilizers decreased in Western Europe and North America in 2000 (Cooper et al., 2011; Cordell et al., 2009) as well. The main reason was the increased awareness of soil saturation (i.e. after the decades of over-use, there was the sufficient phosphorous stock in the soil so that the application rates could be reduced). Furthermore, since 2000, the awareness of eutrophication has also reduced phosphate demand in the developed world aimed at the reduction of leakage to waterways (Scholz et al., 2014). These aspects are the main causes why phosphorus flow decreased at the beginning of the simulation period covered by this study. Restrictions on the use of phosphates in detergents affect wastewater treatment efficiency. However, the rising demand for phosphorus results in an upward energy consumption and, consequently, in the increased GHG emissions. The GHG emissions will reach a maximum of approximately 107 mt CO_2e in 2047. Calculation shows that the annual mean of GHG emissions from the recycling stage is around 97 mt CO_2e between 2000 and 2050. This result implies the impact of benefits resulting from systemic approach to the recycling stage, which shed light on the needs of other policies aimed at controlling phosphorus cycle to prevent environmental problems.

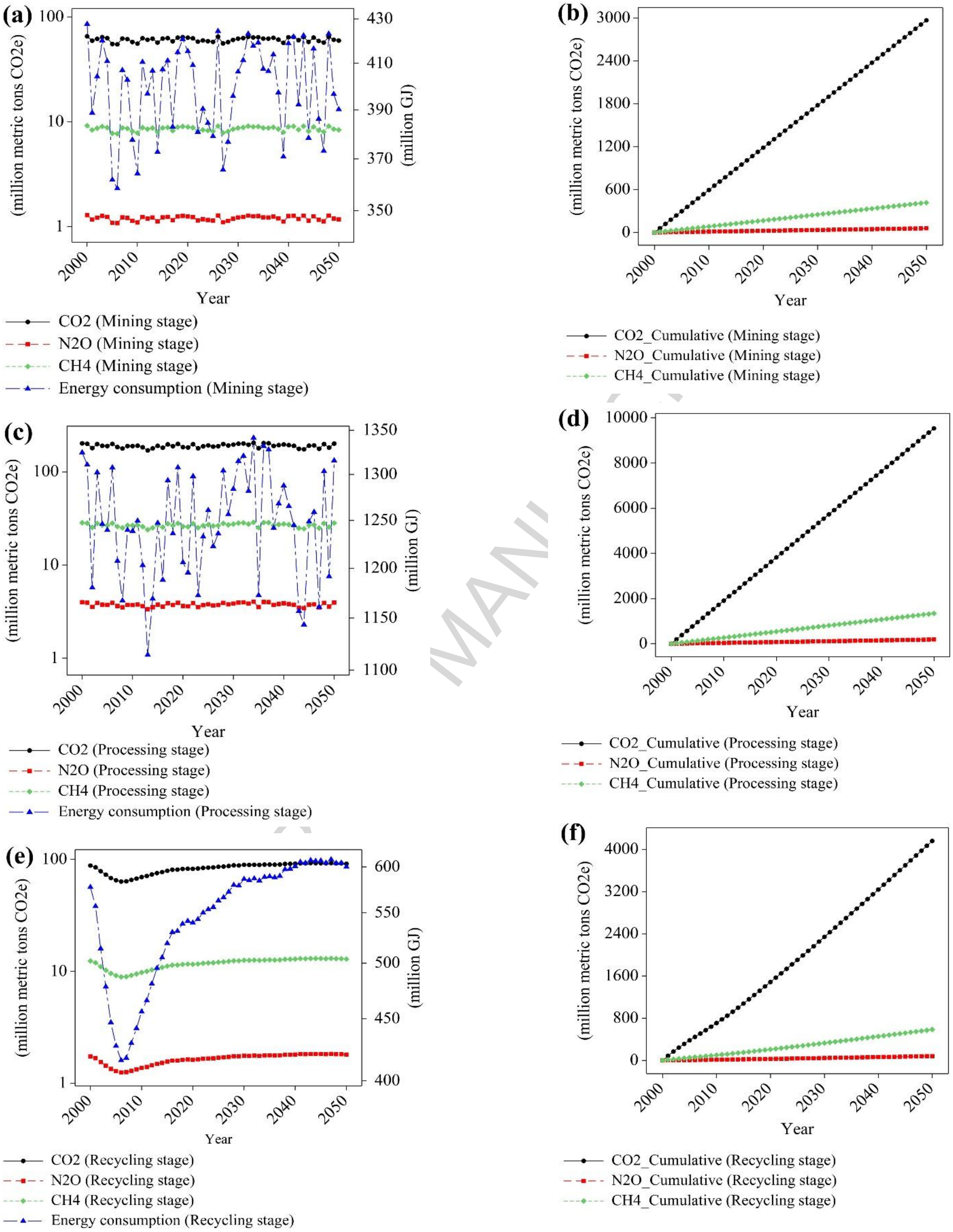

Figure 3. Greenhouse gas emissions and energy consumption levels in the life cycle stages of phosphorus (2000-2050). (a): Mining stage (annual). (b): Mining stage (cumulative). (c): Processing stage (annual). (d): Processing stage (cumulative). (e): Recycling stage (annual). (f): Recycling stage (cumulative).

Results presented in Figure 4 show that, assuming we use the current technology, the processing stage will be the major energy consumer and the biggest GHG emitter in the years 2000-2050. Interestingly, over the same period of time, phosphorus recycling is characterized by higher energy consumption and GHG emissions than mining. Therefore, mining or substitution of phosphorus still have to be considered as important alternatives to recycling if environmental sustainability is to be achieved in the years 2000-2050.

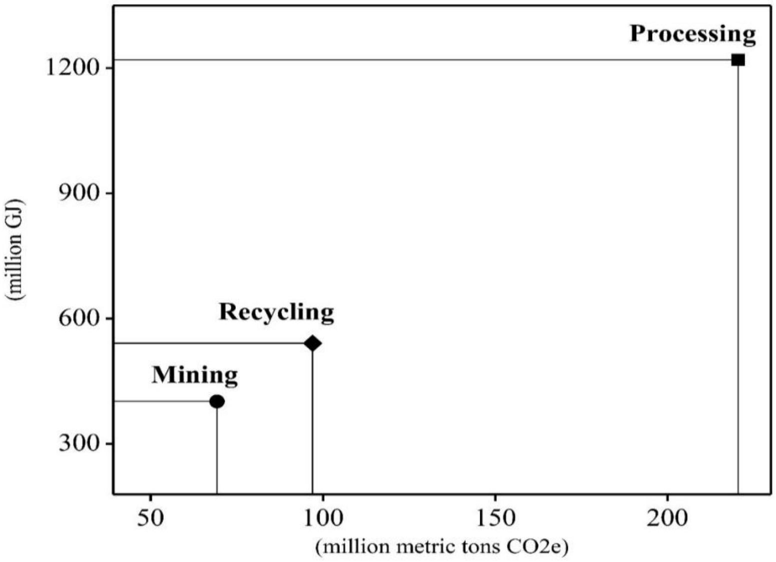

Figure 4. Annual mean of greenhouse gas emissions and energy consumption in phosphorus life cycle in years 2000-2050.

In the recycling stage, phosphorus recovery from two main waste streams including wastewater and manure is analyzed in detail. The processes of phosphorus recovery from wastewater assumed anaerobic digestion. In manure recycling, main processes are solid-liquid separation and anaerobic digestion as well as drying and small-scale incineration (Nättorp et al., 2019). Figure 5 presents the relation between the amount of phosphorus recycled and CO_2e emitted when recycling phosphorus from both sources. Manure recycling provides around 82% of total recycled phosphorus from various sources while wastewater recycling provides only 2% (Figure 5). At the same time, the amount of GHG emitted in wastewater recycling is about 70% of total CO_2e emissions in the recycling stage. The presented result shows inexpediency of recycling phosphorus from wastewater if only the amount of the recycled phosphorus and GHG emissions would be taken into account. However, it is obvious that the removal of phosphorus from wastewater must be done because of a different reason. Excessive presence of phosphorus in water causes eutrophication, and eventually leads to the collapse of ecosystems (Xu et al., 2017; Liu et al., 2012; Chen and Graedel, 2016; Bradford-Hartke et al., 2015).

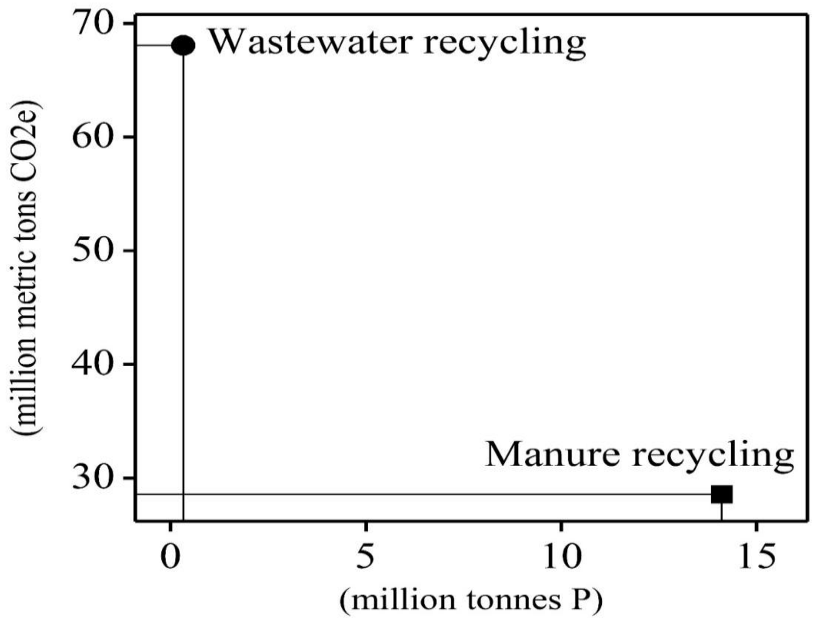

Figure 5. Environmental issues of wastewater and manure recycling (2000-2050).

4. Scenario of Phosphorus Consumption

Dynamic models are often used to study the behavior of a system when demand, supply, and other conditions are changing. The studies of scenarios developed for various situations are especially useful in this case. In the paper (El Wali et al., 2018), we analyzed several options for the improvement of phosphorus recycling. In this study, the proposed model is used to evaluate different scenarios of phosphorus consumption and its global environmental impact in the years 2000-2050. The objective is to explore the impact of future global phosphorus consumption on GHG emissions. Knowledge about this impact is essential for making decisions aimed at reducing GHG emissions.

Changes in phosphorus supply and demand resulting from various factors have been studied extensively (e.g., livestock production (Bouwman et al., 2013) together with demand for phosphate fertilizers, food supply chain (Cordell et al., 2009), and the effect of increasing world population (Shu et al., 2006)). One of the main challenges in phosphorus supply chain management results from increased production of food and fertilizers, e.g. the overall food production is estimated to increase by around 70% until 2050 (Fraiture, 2007). The problem consists in limited resources of phosphate rock as well as non-substitutive character of phosphorus (Ye et al., 2017, Edgerton, 2009). Therefore, phosphorus recovery is very important as a solution that may help manage its shortages in the future. On the other hand, an increase in the production of phosphorus requires more energy and generates more waste and GHG emission in all stages of its supply chain. Given the main objective of this paper, we analyze various scenarios of phosphorus consumption in order to assess its impact on GHG emissions at each stage of the supply chain until 2050. When building the scenarios we assumed that all parameters remain constant except the amount of phosphorus in production and recycling processes.

In this work, four situations have been studied: scenario A - current level of phosphorus consumption as well as B, C and D scenarios representing the cases of 10%, 30% and 40% increase in phosphorus consumption, respectively. The main reason why we have considered this value range, 10-40%, is the technological feasibility of economically justified phosphorus recycling. The probability of obtaining phosphorus from economically sound recycling reaches 40-50% in the next 12-15 years (El Wali et al., 2018; Scholz and Wellmer, 2018).

The results obtained in scenario B compared to those in scenario A represent, on average, 9% and 27% increase in GHG emissions from mining and recycling stages of phosphorus supply chain respectively, whereas emissions remain the same throughout the processing phase (Figure 6 (a-b)). In scenario C, by increasing the consumption of phosphorus by 30% we induce exponential growth of environmental problems in the recycling stage (Figure 6 (c)). Therefore, in this case, recycling should not be recommended as a method ensuring sustainable supply of phosphorus in a long-term perspective. Scenario C shows that GHG emissions from recycling increase by around 49% while the mining stage emits about 23% more than in scenario A. Exponential growth of environmental problems caused by phosphorus recycling intensifies in scenario D (Figure 6 (d)). The analysis of the results demonstrates that the growth in global phosphorus consumption slowly increases environmental problems throughout the mining stage and exacerbates them in the recycling stage, which is going to be a major problem. This result highlights the need for a strategic decision on the development of technologies for phosphorus recycling and a clear need for careful planning of the recycling process.

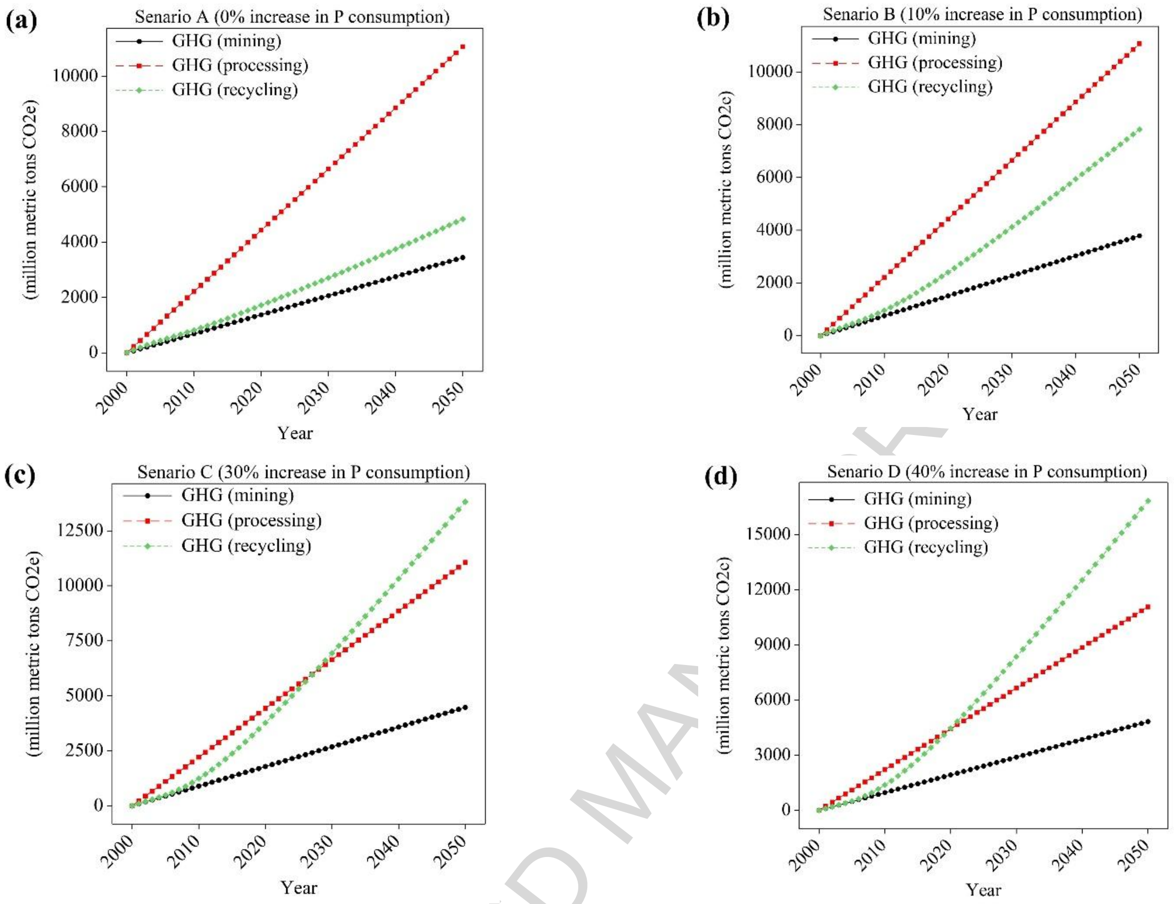

Figure 6. Changes of greenhouse gas emissions from phosphorus supply chain in different scenarios (2000-2050).

The significance of phosphorus recycling is obvious from a material flow perspective. However, several important limiting factors such as environmental issues (energy consumption and GHG emissions) should be considered when analyzing future options of recycling. Previous studies focused on the environmental impact of P recovery technologies by comparing different alternatives, e.g. Sandars et al. (2003) for livestock manure, Buratti et al. (2015) for solid waste, and Spångberg et al. (2014), Amann et al. (2018) and Ye et al. (2017) for wastewater. This paper presents a system dynamics model to analyze energy consumption and GHG emissions (CO_2, N_2O, CH_4 emissions) within the phosphorus supply chain over a 50-year time horizon. We examined three stages of the supply chain: mining, processing & production, and recycling. The main flows in the model were: at the mining stage, the extraction process of phosphate ores; in production, manufacturing fertilizers and animal feed; and in recycling, phosphorus recovery from manure, dry waste and wastewater.

The material flow analysis of this study shows that most of the recycled phosphorus comes from manure (e.g., around 14 million tons in 2013). This result supports previous research of the phosphorus supply chain. Scholz & Wellmer (2015a) estimated that the amount of manure used for soil fertilization ranged between 15 and 20 million tons P in 2011. Results obtained in this research show around 14.3 million tons P in the same year. Results of this paper also confirm previous findings indicating high energy demand and consequently large GHG emissions from the recycling stage of phosphorus supply chain. Results of this paper support findings highlighted by Amann et al. (2018) for the recovery of phosphorus from sewage sludge and Egle et al. (2016) for its recovery from wastewater and sludge treatment systems; as well as considerable GHG emissions from sewage sludge treatment noticed by Piippo et al. (2018).

5. Limitations of the study

Even though phosphorus is predominantly used in agricultural production, analysis of energy consumption for other uses was not considered (i.e. detergent production, other chemical uses) due to the lack of data.

6. Conclusions

Some important environmental issues such as high energy consumption and greenhouse gas emissions need to be addressed to ensure environmentally sustainable phosphorus supply chain. This article gives a comprehensive overview of various flows in phosphorus supply chain from the perspective of environmental sustainability.

In this paper, the obtained results show that the majority of recycled phosphorus comes from manure (around 82%). However, a detailed analysis of environmental issues shows that around 70% of GHG emissions in phosphorus life cycle originates from wastewater treatment process, which provides only around 2% of total phosphorus. This finding highlights the need for new strategies of recycling management as well as a need for the improvement of recycling technologies, especially for the recovery of phosphorus from wastewater. Any technology development for phosphorus recovery should take into account the environmental impact of the process and not just consider technical feasibility of recycling.

Moreover, the analysis of different scenarios shows that the increase in global phosphorus consumption slowly increases environmental problems in mining, which intensify in the recycling stage. It creates a major problem in a longer perspective, which, from environmental perspective, produces unsustainable phosphorus supply chain.

Therefore, there is a clear need for a careful analysis of strategy of phosphorus recycling. Moreover, mining of phosphorus still has to be considered as an important alternative to recycling if environmental sustainability is to be achieved in the years 2000-2050.

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Competing financial interests

The authors declare no competing financial interests.

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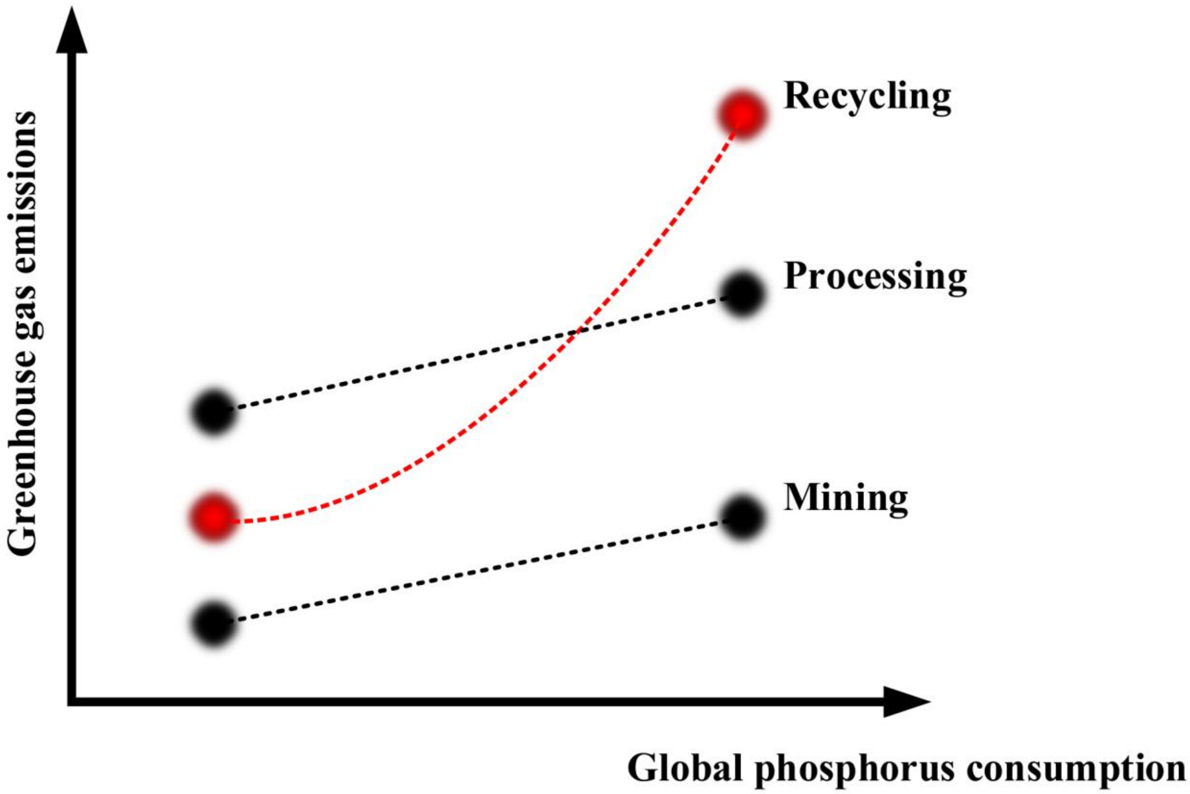

Graphical abstract

HIGHLIGHTS

- Dynamic model for analyzing energy consumption and GHG emissions of phosphorus flow
- Assessment of possible amount of phosphorus to be recovered from wastes
- Assessment of environmental sustainability of phosphorous recycling (2000-2050)
- Impact of current and future phosphorus consumption on the amount of GHG emissions