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Toward a decision support framework for sustainable phosphorus management: A case study of China

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A B S T R A C T

Phosphorus is an essential nutrient for plant growth, as well as a critical element involved with biological metabolism. Current phosphorus utilization efficiencies in most counties are below 20%, which results in significant phosphorus loss and brings severe environmental challenges. Therefore, phosphorus flow management and recovery technologies are of great importance for global sustainable development. However, there is little research available to link up phosphorus flow management and recovery technology development. This paper proposed a systematic, hierarchical framework based on fuzzy comprehensive evaluation (FCE) to identify cost-effective waste streams and suitable technologies for efficient phosphorus recovery, while China is used as a case study to demonstrate its effectiveness. Within this framework, substance flow analysis (SFA) is used to track phosphorus flows in China, and different indicators covering phosphorus quantity, process economics, product safety and their environmental impacts were considered. By using FCE, these indicators were combined into a single score for decision making. Principal component analysis (PCA) was further incorporated to identify barriers and directions for future research and development. Although the data collection was still a challenge, the preliminary insights demonstrated that phosphorus recovery from livestock urine in China is the most cost-effective solution. The framework not only supports decision-makers to formulate national and international phosphorus policies and thus improve global sustainability, but also could be applied to other resources management such as nitrogen and rare earth elements in the future.

1. Introduction

Phosphorus (P) is essential for modern agriculture. Nowadays, almost all phosphorus being consumed are originated from phosphate rock mines located in Morocco, China, Algeria and the USA (Cordell et al., 2009; Wang et al., 2018a,b). However, the US and China used much of their phosphate internally with increasing limitations on phosphate rock export (Lun et al., 2018).

While the world's phosphorus supply is sufficient for the next 50 years (Cordell et al., 2011; Li et al., 2018), its uneven geographical distribution creates political and economic risks. This is especially severe for developing countries, where fertilizer is a major cost for food production (Powers et al., 2019). Moreover, the current phosphorus utilization efficiencies in most counties are below 20% (Li et al., 2015; Lun et al., 2018). Such significant phosphorus loss causes severe algal blooms and eutrophication in the surface water. Smith et al. (2010) reported that algal blooms in Lake Erie alone will cost Canada $5.3 billion if no proper actions are taken. Therefore, understanding and managing phosphorus resources are of great importance for global sustainable development.

To mitigate the above-mentioned challenges, tremendous efforts have been made to quantify phosphorus cycles at global (Villalba et al., 2008; Liu et al., 2008; Chen and Graedel, 2016), country (Klinglmair et al., 2015; Li et al., 2015; Álvarez et al., 2018; Wang et al., 2018a,b; Chowdhury et al., 2018), regional (Senthilkumar et al., 2012; Coppens et al., 2016; Wironen et al., 2018), city (Pearce and Chertow, 2017; Treadwell et al., 2018) and

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even watershed (Jiang and Yuan, 2015; Chen et al., 2017) scales. These studies reveal the nature and magnitude of phosphorus consumptions and wastages in different sub-systems. On the other hand, phosphorus recovery has excellent potential to mitigate the environmental consequences of phosphorus loss. There have been more than 30 phosphorus recovery technologies reported in the scientific literature (Cieslik, B., Konieczka, P., 2017). However, many of them are still encountering difficulties with commercial implementation in terms of technology readiness level, process economics, and environmental risks (Li et al., 2019).

The growing complexity of phosphorus cycles and the increasing numbers of phosphorus recovery options (i.e. from different waste sources using different technologies) make it challenging to choose cost-effective waste streams for the commercialization of phosphorus recovery technologies (Li et al., 2020a). For example, phosphorus plant availability in iron-treated chemical sludge may not be as active as that in animal farming effluent, also, swine wastewater may have higher heavy metals and antibiotics content that will increase the biological risks of the recovered products (Huang et al., 2019). These facts indicate that it is necessary to pay more attention to the linkage between phosphorus flow management and those available recovery technologies (Li et al., 2020a). Unfortunately, there is currently no research considering such complexity for phosphorus recovery, and this has been identified as a research gap. More studies on the economic, social and environmental aspects of a phosphorus recovery system should be conducted. Such studies are challenging due to limited awareness of the phosphorus crisis, the complexity of phosphate species in various waste, and the large number of complex technologies.

To select the most cost-effective streams for resource recovery, different aspects of each alternative, as well as all the associated disadvantages and advantages in terms of environmental, social, economic and technical issues should be evaluated (Gu et al., 2019). In general, different techniques such as life cycle analysis, material flow analysis and multi-criteria decision making have been established and applied to select appropriate options for resource management (Khoshand et al., 2019). The cost-benefit analyses have also been widely used to either increase the material recovery efficiency or to reduce the waste for landfilling or incineration, while some studies also incorporate environmental or externalities or socio-economic implications (Gregory et al., 2008). However, existing resource management studies mainly focus on specific geological or operational characteristics, while the variations from biogeochemical, socio-economical, cultural and political factors make the specific findings and policies developed in one region not applicable to another.

Compared with the above-mentioned evaluation methods, fuzzy comprehensive evaluation (FCE) is more sensitive due to its predefined weights and reduced fuzziness by configuring suitable membership functions (Xie et al., 2017). FCE method is a fantastic decision-making tool as it can manage the complicated decision-making problems where both quantitative and qualitative aspects are considered (Wang et al., 2018a,b). The fuzzy theory has been developed to address the fuzziness of decision-making problems, by allowing decision-makers to express preference through fuzzy number to the judgement (Nabavi-Pelesaraei et al., 2019). For example, Khoshand et al. (2019) applied a fuzzy analytical hierarchy model to choose the best electronic waste collection system based on economics, operational, strategic and social criteria. Xie et al. (2017) developed an FCE method to evaluate environmental quality in commercial swine buildings by considering factors such as temperature, humidity, and concentrations of NH_3, CO_2 and H_2S.

In this paper, a comprehensive and uniform framework based on FCE for phosphorus management was proposed to select cost-effective streams for phosphorus recovery and to identify barriers for future research. By using this framework, the balance between social, environmental and economic factors during resource recovery could be clarified, and the phosphorus assessment across different countries and regions can be compared on the same basis. Moreover, the framework will support decision-makers to formulate national and international policies and thus improve global sustainability.

2. Methodology

A systematic, hierarchical framework based on FCE was developed by considering the total amount of phosphorus that could be recovered, plant availability and human health risk assessment. The process economics and environmental emissions for different phosphorus recovery technologies were also included. Principal component analysis (PCA) was further incorporated to identify barriers and directions for future research. Fig. 1 is an overview of the framework, which is further tested using China as a case study, with the results being shown in Section 3.0.

2.1. Plant availability analysis

To determine suitable waste streams for resource recovery, the first step is to evaluate its overall quantity to determine the market size. In terms of phosphorus recovery, substance flow analysis (SFA) is always used. However, common SFA ignored the plant availability of the recovered phosphorus, which might overestimate the amount of phosphate that could be recovered. That is to say, the phosphate species vary in different waste streams, and some are not immediately available to plants. For example, Krogstad et al. (2005) documented that chemically precipitated sewage sludge has relatively low fertilization effects as most phosphate is immobilized after the treatment. Therefore, the plant availability analysis was integrated with SFA to determine the phosphorus quantity in different waste streams.

2.1.1. Substance flow analysis

SFA is an important tool to study the circular economy and to devise material flow management. It tracks the flows and stock of a substance across the social-economic system by considering the mass balance and considering the core methods of industrial ecology, anthropogenic and industrial metabolism. Since 1990, SFA has been successfully applied to study material, substance or product flows across different industrial sectors or within ecosystems. More information about constructing an SFA model could be found in our previous paper (Li et al., 2015, 2019a).

2.1.2. Plant availability evaluation

In the proposed framework, the concept of relative agronomic phosphorus efficiency (RAE) was used to quantify the amount of plant-available phosphorus based on the result from SFA. RAE is an established indicator when comparing the fertilization effectiveness of recycling products with mineral fertilizer. It differs from the phosphorus use efficiency (PUE) used in soil science because RAE uses water-soluble mineral fertilizer as the reference and thus is more comparable for phosphorus from different secondary flows, while PUE strongly depends on local soil conditions. Commonly, the RAE of mineral fertilizer is defined as 100%, while the RAEs of recycled products were determined by growth experiments (Hamilton et al., 2017) or from the literature. For a detailed explanation of how RAE is defined, please refer to Hamilton et al. (2017).

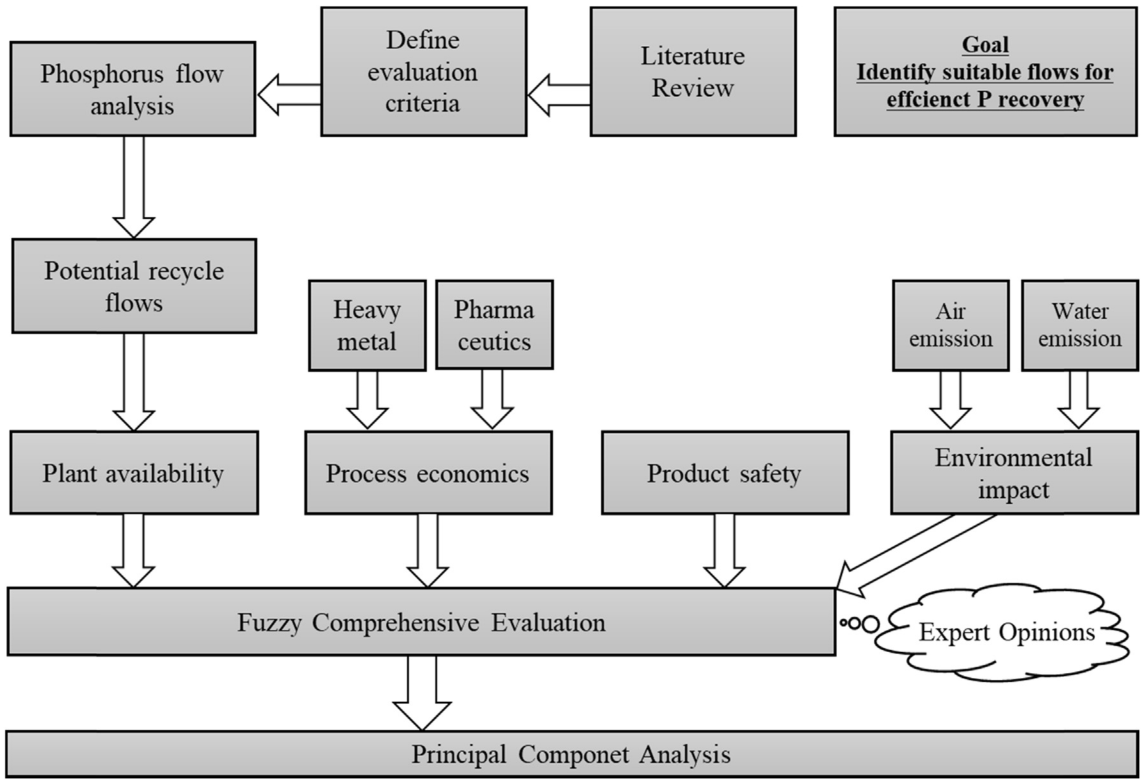

Fig. 1. Proposed phosphorus management framework.

2.2. Product safety evaluation

The recovered phosphorus products may become a secondary pollutant if it is from a high biological risk stream (e.g. high heavy metal or tetracycline concentration). The reuse of these products will then cause risks to agricultural land and human beings. Therefore, soil pollution index and human health risk index were used to represent the biological risks of recovered phosphorus from different waste streams.

2.2.1. The soil pollution index

Heavy metals in the secondary phosphorus might pollute the agricultural land when being used as fertilizer. Previous research (Li et al., 2018) suggested that the Nemerow integrated pollution index (PN) is a useful indicator to quantify such impact from multiple toxic elements, which could be derived using the following equation:

$$PN = \sqrt{\frac{(P_{iave})^2 + (P_{imax})^2}{2}} \tag{1}$$

where, P_i is the single pollution indices of each heavy metal, P_{iave} is the average of P_is for deferment heavy metals, P_{imax} is the largest Pi among all P_is. P_i can be calculated as the following:

$$P_i = \begin{cases} C_i/x_a & C_i \leq x_a \\ 1 + (C_i - x_a)/(x_c - x_a) & x_a \leq C_i \leq x_c \\ 2 + (C_i - x_c)/(x_p - x_c) & x_c \leq C_i \leq x_p \\ 3 + (C_i - x_p)/(x_p - x_c) & x_p \leq C_i \end{cases} \tag{2}$$

where, C_i is the toxic element concentration in the soil with a unit of mg/kg, x_a, x_c and x_p are the threshold, the low and high concentration levels required by the Environmental Quality Standard for Soils (published by the National Environmental Protection Agency of China, GB15618-2018).

2.2.2. The human health risk index

Various pollutants such as heavy metals, antibiotics and pharmaceutics in the secondary phosphorus may expose to humans through i) inhalation using the mouth and nose (ADI_{inh}), ii) absorption of particles adhered to exposed skin (ADI_{skin}) and iii) direct digestion through food (ADI_{dig}). In the proposed framework, such effects were quantified by USEPA model, with corresponding parameters from the work of Li et al. (2018) and Chen et al. (2018). The average daily intake (ADI, mg/d) could be calculated using the equation below:

$$ADI = ADI_{inh} + ADI_{skin} + ADI_{dig} \tag{3}$$

Equations used to quantify risks from different pathways were given below:

$$ADI_{inh} = \frac{CS \times IR_{air} \times EF \times ED}{PEF \times BW \times AT} \tag{4}$$

$$ADI_{skin} = \frac{CS \times SA \times AF \times ABS \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{5}$$

$$ADI_{dig} = \frac{CS \times IR_{soil} \times EF \times ED}{BW \times AT} \times 10^{-6} \tag{6}$$

where, CS is the concentration of each pollutant. IR_{air} and IR_{soil} are the ingestion rate through air and soil, m^3/d. EF, ED an AT are the exposure frequency, the exposure duration and the average year of expose. PEF is the particle emission factor, BW is the average body weight, SA is the surface area of the skin that contacts that soil, ABS

the dermal adsorption factor and *AF* is the adsorption coefficient. All values are obtained from the work of Li et al. (2018) and Chen et al. (2018).

2.3. Process economics and environmental evaluation

The success of a recovery system depends not only on its quantity and safety but also the process economics and environmental footprint. Due to the data availability and the maturity of various technologies, composting and struvite crystallization are used as secondary phosphorus recovery technologies from the solid and liquid phase, respectively. For both technologies, land and building costs are ignored during capital cost analysis. The composting is based on a labour-intensive plant using an open window (capacity is 6.5 tonnes per day). The compost is sold to the market while the other fractions are dumped (Aye and Widjaya, 2006). The struvite crystallization process is based on a pilot plant located in Veneto region, Italy, with an average flow rate of 15.5 m^3 per day and the operating pH between 8.0 and 8.5 (via CO_2-stripping) in a fluidized bed reactor. The resulting liquid is partially recycled to the stripping columns, while the final effluent returns to the head of the plant (Rodriguez-Garcia et al., 2014).

The recovery of phosphorus will introduce additional liquid and gas emissions. During composting, organic wastes were decomposed and released mainly as CO_2 and H_2O, while NH_3, N_2O and N_2 could also be generated from the nitrogen decomposition. The greenhouse gas effect from these components could be determined following the greenhouse effect of a 50-year time horizon (Rodriguez-Garcia et al., 2014). The greenhouse gas emissions of struvite crystallization should be lower because this is mainly a solid-liquid phase chemical precipitation process with no gas release. Its primary emissions are from equipment manufacturing, chemical and electricity consumption. The environmental effects of leachate from both technologies could be quantified by the acidification and eutrophication potential, which is commonly derived from the BOD, COD and NH_4^+ concentrations in life cycle analysis.

The environmental footprint analysis mainly considered the recovery process but ignoring its positive contribution of replacing the currently applied mineral fertilizer due to data limitation. Main information used for the environmental evaluation was obtained from the work of Aye and Widjaya (2006), and Rodriguez-Garcia et al. (2014). The greenhouse gas emission of 320 and 187 kg CO_2 for per ton waste being processed were used for composting and struvite crystallization, while the BOD, COD and NH_4^+ emission were 81 and 38, 137 and 56, 36 and 24 g of per ton processed waste, respectively.

2.4. Fuzzy comprehensive evaluation

The balance between technical, economic, social and environmental considerations makes the identification of cost-effective flows for phosphorus recovery difficult. By defining the preferred weights of different indexes, FCE combines all indexes into a single score to provide an overall evaluation of objects (e.g. suitable flows for phosphorus recovery) that are subject to these indexes (e.g. plant availability or operational cost). Here, a multilayer FCE system was proposed and was then combined with defined weights from an expert survey to calculate the scores of different waste streams for phosphorus recovery.

2.4.1. The index system

Based on the literature review (Li et al., 2018; Rahman et al., 2019), and the interview with experts in the phosphorous recovery field, the primary concern of adapting a phosphorous recovery technology includes the total amount of phosphate that could be recovered, process economics, product safety and its corresponding environmental impact. Similarly, 12 secondary indexes were selected and shown in Table 1.

2.4.2. FCE model

The FCE was developed by introducing an indicator set $U = \{u_1, u_2, \ldots, u_m\}$ and a remark set $V = \{v_1, v_2, \ldots, v_n\}$. In the proposed framework, *U* represents the indexes (size of U is 16 × 1), *V* is the potential secondary phosphorus for reuse and recovery (size of V is 12 × 1). FCE was to provide a mapping from *U* to *V*, namely, $U = b \times V$, where *b* is the fuzzy transformation $b = R \times a$ (size of *b* is 16 × 12). *a* is a symmetric matrix representing the weight of each indicator U_m, which is obtained from an expert survey including twenty-five experts from Tsinghua University, Yanshan University, Nanyang Institute of Technology and Dongguan University of Technology (size of *a* is 12 × 12). *R* is the fuzzy evaluation matrix signifying a mapping from the index hierarchy to the remark set (size of *R* is 16 × 12). It is a matrix of various indicators for different potential secondary phosphorus calculated from section 2.1, 2.2 and 2.3, and can be written as:

$$R = \begin{bmatrix} r_{11} & r_{12} & \ldots & r_{1n} \\ r_{21} & r_{22} & \ldots & r_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ r_{m1} & r_{m2} & \ldots & r_{mn} \end{bmatrix} \tag{7}$$

r_{mn} is the membership function, *h(I)*, of each remark. To make different indicators comparable, R could be standardized by using the following equation,

$$h(I) = \begin{cases} I & when\ 0 < I < 1 \\ e^{1-I} & when\ 1 < I \end{cases} \tag{8}$$

I is a sub-membership to eliminate the data imbalance caused by units and values of different indicators.

$$I = \begin{cases} \dfrac{C_i}{S_i} & \textit{for indexes where larger value is prefered} \\ \dfrac{S_i}{C_i} & \textit{for indexes where smaller value is prefered} \end{cases} \tag{9}$$

where, S_i is the base value, which equals to the maximum value of an index when a larger value is preferred (e.g. effective phosphorus that could be recovered from a flow), or equals to the minimum value of an index when a smaller value is preferred (e.g. the operational cost and the CO_2 emission). C_i is the value of indexes calculated in Section 2.2.

2.5. Principal component analysis

PCA can extract the main feature of a dataset through transforming the original data into a set of linearly independent representations using a linear transformation, which is achieved by ignoring the less important principal components while retaining the lower-order components that can represent the most important aspects of the data. It is widely used in demography, quantitative geography, molecular dynamics simulation and mathematical modelling. However, since PCA relies on the given data, the accuracy of the data has a significant impact on the analysis results. A General PCA procedure could be found from the work of Li et al. (2019).

2.6. Case study

In the proposed framework, an SFA structure based on our

Table 1
Proposed indexes for the fuzzy comprehensive evaluation.

First-level	Second-level	Symbol	Definition	Unit
Quantity	Plant availability	A	Effective phosphorus for plant uptake	1000 kt P
Process economics	Operational cost	B	Daily maintenance and administration cost of a recovery unit, for per ton waste being processed	$
	Capital cost	C	Fixed and one-off expenses for a new unit, land and building cost are excluded	$
	Product price	D	Resell price of the recovered product	$
	Degree of intensification	E	The density of the recovery units	%
Product safety	The heavy metal pollution index	F	To identify the exposure and assess the risk to soil land	–
	Human health risk of heavy metal	G	To identify the exposure and assess the risk to humans	–
	Human health risk of antibiotics	H	To identify the exposure and assess the risk to humans	–
Environmental impact	CO_2 emission	I	To indicate the global warming potential of per tonne waste being processed	kg
	BOD emission	J	To indicate the water pollution potential of per tonne waste being processed	g
	COD emission	K	To indicate the water pollution potential of per tonne waste being processed	g
	NH_4^+ emission	L	To indicate the water pollution potential of per tonne waste being processed	g

previous research (Li et al., 2015, 2019a) were used while applying phosphorus flows in China as a case study. The geological boundary was the mainland of China with the base year of 2015. Hong Kong, Taiwan, Macao and marine environments were excluded due to a large amount of missing data in the current literature. For consistency, all phosphorous flows and stocks were measured in thousands of tons of elemental phosphorous.

RAE values from the work of Brod et al. (2015a, b), Hamilton et al. (2017), Liu et al. (2017)a,b and Václavková et al. (2018) were used by assuming that recovered phosphorus using different technologies have similar RAEs. While we acknowledge that the fertilization efficiency of recovered phosphorus varies across different waste streams over the season, the relative numbers should still be able to demonstrate the usefulness of the proposed framework.

3. Results and discussion

3.1. Main phosphate flows in China

The considerations of technical, quality and quantity aspects are important during phosphorus recovery. The total amount of phosphorous being produced, recycled and processed for different industries in China in 2015 was shown in a Sankey diagram in Fig. 2, where the width of flow is proportional to its value. The dash lines do not necessarily reflect the actual allocation of flows, but the potential secondary phosphorus flows where recovery and reused could be implemented. As can be seen, total phosphorus consumed in 2015 is 9111 kt, with nearly 70% being sourced from phosphate rock mining, and the rest from the importation of crops, meat and phosphate rock. The total exported phosphorus is 799 kt, where chemical fertilizer domains this category. The difference between import and export leads to a phosphorus accumulation of 7080 kt. Such significant accumulation is further investigated by calculating the phosphorus residues in unbalanced stocks in the SFA system, indicating that 46.7% phosphorus ends up in the landfill waste, 24.6% goes to the wastewater treatment, 11.1% is discharged to natural waterways without proper treatment, and the rest is accumulated in the cultivated land and non-food industry. It should be noted that the non-food sector is a complex subsystem, involving phosphorus flows as with the biodiesel production from crops (GM) and animal fat (JM), as well as the manufactured furniture and consumable commodities. Due to the lack of information regarding the destinations of these products, they were assumed to be accumulated in this sector. More detailed phosphorus flows analysis in China and discussions could be found in our recently published papers (Li et al., 2019a, 2020b).

China's phosphorus consumption relies on phosphate rock mining, which is of great concern when considering resource urgency and its associated environmental pollution. The reuse of livestock manure and crop residuals onto the cultivated land has been implemented for a long time, and are still vital flows for efficient phosphorus management. However, the growing environmental awareness, increasing labour costs and decreasing fertilizer price make chemical fertilizer a primary nutrient source, while wasted phosphorus in those flows is climbing. Moreover, the increasing of wastewater treatment facilities and the transformation of intensive livestock farming make phosphorus management and recovery easier in those flows. Such a trend difference might affect the results of the proposed framework and is thus recommended to be investigated in future research. The potential secondary flows are highlighted in Fig. 2, with their definitions and values being shown in Table 2. The phosphorus-rich flows can be divided into solid and liquid phases, where different processing technologies are required for reused and recovery. As can been seen, flows associated with the solid phase contains more phosphorus than the liquid phase. However, research on phosphorus recovery is mainly focusing on the liquid phase due to its low cost and high efficiency (Li et al., 2018).

RAEs of different secondary phosphorus flows are also presented in Table 2, where the data is chosen over absolute metrics for fertilization effects. Due to the data limitation and the fact that this case study is mainly to demonstrate the usefulness of the proposed framework, those values are adopted from various literature and were assumed to be representative of China's conditions. They are then multiplied by phosphorus in secondary flows from SFA, to obtain the amount of plant-available phosphorus. The current study assumes China and other counties have similar RAEs, which might not be true as they are very dependent on the treatment technology. For example, biologically treated sewage sludge has a vastly different RAE value from chemically (e.g. Al-precipitated) treated sewage sludge. In other words, the plant availability is a function of both the secondary P resource and the technology, indicating that further investigation of RAE is required to make the case study close to China's real situation.

3.2. Results from FCE

Typical concentrations of heavy metals, pharmaceuticals and antibiotics from different secondary phosphorus flows were collected from the literature and shown in Appendix 1 and 2. To collect expert opinions from different disciplinary, twenty-five experts specialized in ammonia removal, struvite crystallization, composting, substance flow analysis, phosphorus management and

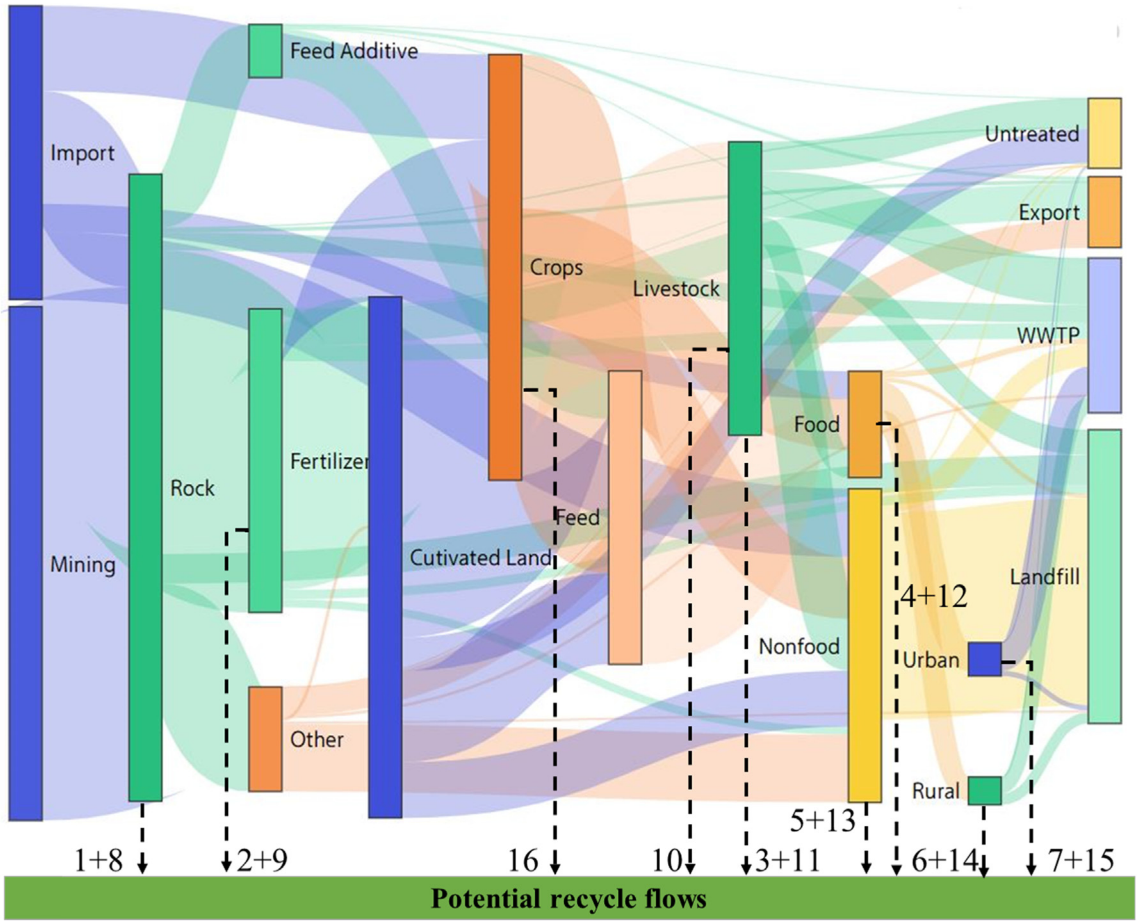

Fig. 2. Phosphorus flows in China (definitions of '1–16' are shown in Table 2).

Table 2
Secondary phosphorus flows being considered and their RAEs.

Phase	Name	ID	Remarks	P amount	RAE	Reference
Liquid	Mining	1	Treated wastewater from phosphate rock mining	172	0.85	Li et al. (2018)
	Fertilizer	2	Treated wastewater from fertilizer manufacturing	149.9	0.85	Römer and Steingrobe (2018)
	Livestock	3	Urine from livestock	439.5	0.85	Brod et al., (2015a); Hamilton et al. (2017)
	Food	4	Treated wastewater from food processing	56.8	0.85	Hamilton et al. (2017)
	Nonfood	5	Treated wastewater from nonfood processing	212.1	0.85	Li et al. (2018); Hamilton et al. (2017)
	Rural	6	Treated wastewater from the rural live	147.4	0.85	Krogstad et al. (2005)
	Urban	7	Treated wastewater from the urban live	268.5	0.85	Krogstad et al. (2005)
Solid	Mining	8	Landfilled waste from phosphate rock mining	114	0.3	Li et al. (2018)
	Fertilizer	9	Landfilled waste from fertilizer manufacturing	36	0.3	Li et al. (2018); Römer and Steingrobe (2018)
	Livestock E	10	Livestock manure returned to cultivated land	1146	0.83	Brod et al., (2015a); Hamilton et al. (2017)
	Livestock W	11	Landfilled waste from livestock farming	96	0.8	Brod et al. (2015b); Li et al. (2018)
	Food	12	Landfilled waste from food processing	22	0.8	Hamilton et al. (2017)
	Nonfood	13	Landfilled waste from nonfood processing	792	0.3	Hamilton et al. (2017); Li et al. (2018)
	Rural	14	Landfilled waste from the rural live	42	0.7	Krogstad et al. (2005)
	Urban	15	Landfilled waste from the urban live	20	0.7	Krogstad et al. (2005)
	Crop	16	Crop residue and waste returned to cultivated land	1824	0.35	Hamilton et al. (2017); Li et al. (2018)

engineering design were invited, and twenty valid questionnaires were recovered. The results are shown in Appendix 3.

In general, the index system for selecting suitable secondary phosphorus flows accurately reflect the current concerns of phosphorus recovery from society. Among these technical performance indexes, the amount of plant-available phosphorus accounts for nearly 40% of the total weight and is a critical factor. Product safety, namely the effect of heavy metals and antibiotics on the environment and human health also attracted significant attention. Degree of intensification also plays an important role when considering the economics of phosphorus recovery. For example, the crops residues involve a large amount of phosphorus, but the phosphorus recovery from this flow is challenging, as its low intensity requires significant labour and transportation investments. In the meanwhile, phosphorus recovery from the wastewater treatment plant is more feasible because it is a hotspot of phosphorus flows in human's food supply chain.

FCE results for first-level indicators are shown in Fig. 3, where x-

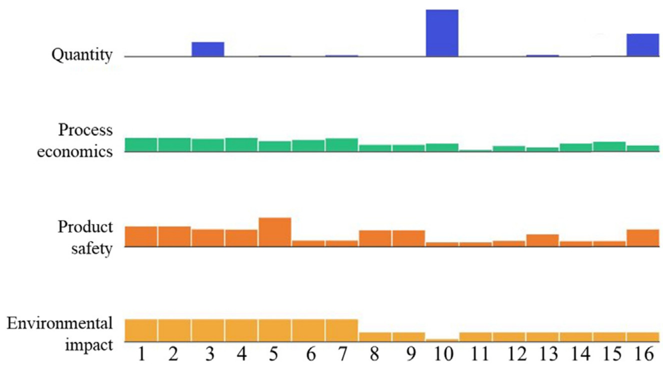

Fig. 3. FCE scores for first layer categorical variables (higher bar plot indicates a higher FCE score).

axis represents the possible secondary flows for phosphorus recovery (definitions of 1–16 are given in Table 2), and y-axis is their relative FCE score. In general, it could also be concluded that phosphorus recovery in the liquid phase is more feasible than the solid phase, especially when considering the process economics, product safety and the environmental effects. According to the first-level indicators, phosphorus recovery and reuse in livestock urine, reused crop and livestock manure ranks the top three. Secondary phosphorus recovery from livestock urine performs well across all first-level indicators, while the livestock manure has an outstanding performance on the amount of plant-available phosphorus, and the recovered product from the reused crop is safer.

The scores of different indicators for each secondary phosphorus flow are shown in Fig. 4, where a large cycle means a high score. As can be seen, crop residue has a high score in terms of phosphorus quantity, but its process cost and environmental footprint are much higher. Phosphorus recovery from phosphate mining and fertilizer manufacturing wastewaters have lower antibiotic risks but higher environmental footprint.

3.3. Principal component analysis

In the proposed framework, PCA was used to compare the effectiveness of different phosphorus reuse/recovery flows to provide suggestions for future research. Indicators from the FCE model were used as variables, and various secondary phosphorus flows (identified in Table 2) were used as observations to construct the PCA model in Matlab. A Pareto chart with the percentage of variance explained by each principal component was shown in Fig. 5, indicating that around 80% of the total variance can be represented by the first two PCs. Therefore, the first two principal components provide sufficient information for the following analysis.

The score plot shown in Fig. 6a indicates clearly that the secondary phosphorus flows could be divided into three groups. The PC1 of all solid phase phosphorus-rich flows are round 2.5 and thus can be categorized into group G1. The liquid phase phosphorus-rich flows are split into group G2 and G3 due to their significant differences from both PC1 and PC2. In PCA, the closer the variables to the axis origin in the loading plot, the smaller the effect it will have on the group difference in the score plot (Li et al., 2015). Therefore, it could be concluded that the differences between G1, G2 and G3 are driven by plant availability (A), operational cost (B) and the capital cost (C). Compare to other secondary phosphorus, the livestock manure (10) and the crop residue (16) returned to the cultivated land have higher plant availability and much lower cost in China. However, crop residue is not an ideal flow for phosphors recovery due to its low degree of intensification caused by the inefficient crop harvesting and processing, as well as the lack of food waste management and recovery system.

Although FCE identified that composting of livestock manure (flow ID: 10) and crop waste (flow ID: 16), as well as struvite crystallization in livestock urine (flow ID: 3) are the most feasible flows for phosphorus recovery, PCA is still useful to discover the reasons for not achieving a better score and thus could give recommendations for future research. From the score and loading plot, it could be found that capital cost and low degree of intensification are main barriers decreasing the resource recovery performance

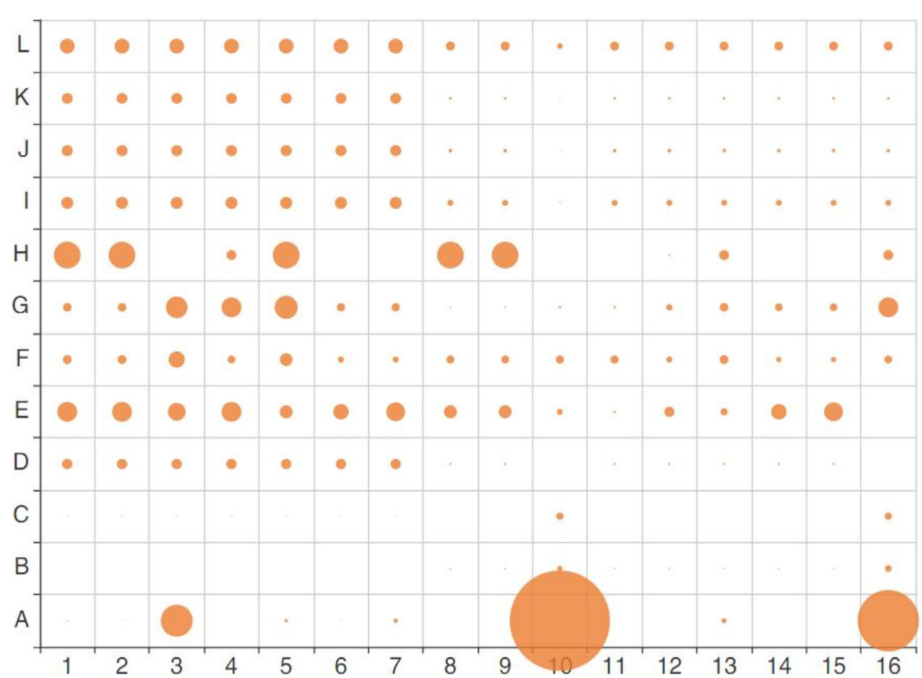

Fig. 4. FCE scores for second layer categorical variables (larger circle indicates a higher FCE score).

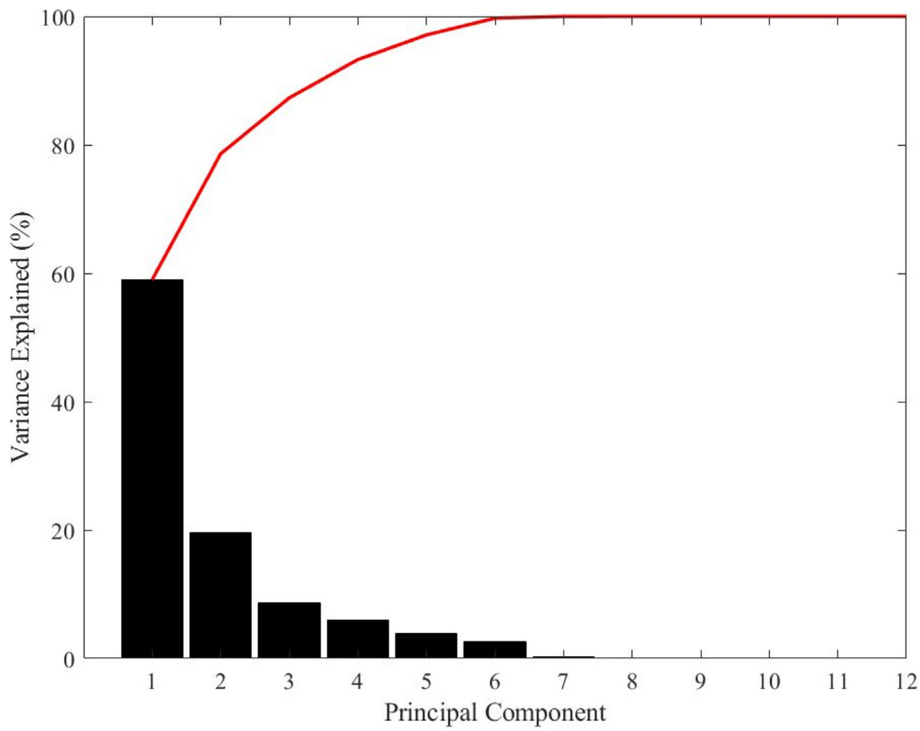

Fig. 5. Percentage variance explained by different principal components.

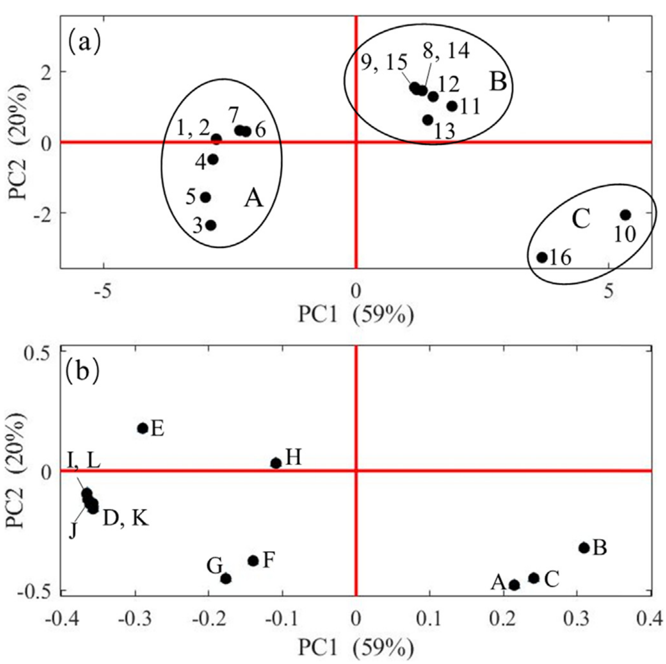

Fig. 6. PCA score (a) and loading (b) plots (definition of 'A to L' in Table 1, '1–16' in Table 2).

from wasted crop and livestock manure composting. In other words, improvement of those barriers would make those secondary phosphorus flows more feasible for phosphorus recovery. Similarly, minimization of antibiotics in livestock urine and heavy metals in most liquid phase phosphorus-rich flows could also improve the phosphorus recovery potential in the proposed framework. Those could then be used to guide future management and research practices. For example, to recover and reuse more phosphorus, reducing the capital cost of composting, and minimizing the effect of pollutants (e.g. heavy metals and antibiotics) should be considered.

3.4. Implications

Currently, there are sufficient understanding of macro-level phosphorus management and micro-level phosphorus recovery technologies. However, there is a gap in integrating multi-level knowledge to design an effect phosphorus recovery process in different countries/cities. Such knowledge could guide the phosphorus recovery practice by highlighting cost-effective flows and technologies. The case study in this research shows that livestock urine is the most suitable secondary phosphorus flow in China. The main reasons are its high amount of plant-available phosphorus, low heavy metal concentration and low ammonia nitrogen emission. The livestock waste transportation was identified as a barrier for cost-effective phosphorus recovery in many countries, where economic incentives and mobile-based recovery unit for enhancing animal waste relocation are suggested. This is currently not a problem for China because of the significant increase of intensive livestock farming, which has become another phosphorus hotspots and makes the phosphorus recovery possible.

It is important to note that the proposed system is new. Therefore, most data used in the case study are adapted from the literature and might make some conclusions unreliable. In fact, it is difficult to draw substantive conclusions about certain aspects of the system performance due to the data uncertainty, which might come from the lack of information/knowledge for certain evaluation criteria and variations from the expert survey. However, the comparison of different secondary phosphorus flows is still important because the framework links the macro-level phosphorus flow management practice and the micro-level phosphorus recovery technology. It will provide critical suggestions for sustainable waste management, identify missing data that should be paid attention to, and figure out gaps for technology development.

Different world visions, understanding of problems, economic status and criteria data can lead to disagreements on how to allocate resources for efficient phosphorus recovery. To address uncertainties within the proposed system for wider applications, specific tools are required to facilitate the eventual implementation of solutions. For example, an RAE database of secondary phosphorus in different soil types would help to make the estimation of plant-available phosphorus more accurate. With this in hand, scientists, farms and the government can quantitatively explore the full suite of feasible flow priorities, and their effect on national phosphorus management. The co-creation between the proposed framework and specific tools could then help to overcome barriers to phosphorus recovery and guide decision-maker for changes at the science-policy interface.

4. Conclusions

Instead of identifying phosphorus recovery streams based on their quantity and technical availability, this paper develops a multi-criteria decision-making framework for sustainable phosphorus management and recovery, where the current gap between phosphorus flow management and recovery technology development could be fulfilled. Various social, economic and environmental indicators were evaluated by FCE to identify the cost-effective waste streams in China. The results indicated that phosphorus recovery from livestock urine was the most suitable waste streams in China. The main reasons are the high amount of plant-available phosphorus, low heavy metal concentration and low ammonia nitrogen emission. The PCA analysis indicates that further reduction of the operating and capital cost of the struvite crystallization, as well as better management of antibiotics associated with this flow, could help improve its FCE score. Development of specific tools and the phosphorus related database are recommended to make full use of the developed framework in the future. Also, the comparison of different countries under the proposed framework, by considering the variations of biogeochemical, socio-economical, and cultural and political factors are suggested for future research.

CRediT authorship contribution statement

Bing Li: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Yue Fei Huang:** Conceptualization, Investigation, Writing - review & editing. **Ping Li:** Methodology, Writing - review & editing. **Wei Yu:** Methodology, Validation, Visualization. **Guang Qian Wang:** Conceptualization, Validation, Resources, Supervision. **Brent Young:** Resources, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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