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Phosphorus in waste sources in Southern Vietnam: potential for recovery

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Abstract

The potential for phosphorus (P) recovery from various sources in Southern Vietnam has been assessed in this study. Five types of waste were studied, namely sediment from catfish pond, manure from cattle and pig farming, and also sludge from domestic and rubber-latex processing wastewater-treatment plants. The study identifies P-reserve and assesses factors related to P recovery from waste sources such as distribution, collection, transportation conditions, and composition of wastes. P-reserve from catfish farming is estimated about 17.7 kt yr^{-1} while reserve from pig farming is the highest, about 21.7 kt yr^{-1}. Total P-reserves from studied wastes are estimated about 50 kt yr^{-1}, equivalent to 37% of Vietnam's imported nutrient P quantity in 2019. Generated sludge from rubber-latex processing wastewater-treatment plants has the highest potential and favorable properties for P recovery. It turns out to be feasible to collect and recover P from this waste source under Vietnam's current conditions.

Keywords Phosphorus recovery, Domestic wastewater-treatment, Catfish farming, Rubber latex processing, Pig farming, Cattle farming

1 Background

Southern Vietnam consists of two main regions: Southeast (SE) and Southwest or Mekong River Delta (MRD). It includes 17 provinces and 2 municipalities in total, of which SE has 5 provinces and one city. As reported of National Environment Status of the Ministry of Natural Resources and Environment (MONRE), there were 98 active industrial parks in the Dong Nai River basin belonging to SE area by the end of June 2018 [1]. According to the General Statistic Office of Vietnam (GSO), the average population density of SE and MRD were 725 and 426 people km^{-2}, respectively [2]. Geographical characteristics such as geology, soil, topography, and socio-economic conditions affect the specific structure of industrial fields and correspondingly the distribution of wastes. The SE region has a higher elevation than the MRD area. Ferralsols, characterized by yellowish-red soil, and Acrisols, characterized by gray soil, occupy approximately 43% and 33% of the land area in SE, respectively [3]. These two main soils are suitable for the development of perennial industrial crops, especially rubber trees, leading to a significant local rubber-latex processing industry in that region. Total land area for rubber culture in the SE in 2017 is about 548,900 ha and total amount of latex harvested is about 777.2 kt [4]. Post-harvest rubber latex is mostly processed locally to produce raw latex materials before exporting or refining plastic products. The MRD is one of the delta plains with the largest area and lowest elevation in the world [5, 6]. Water from the Mekong River flows through 6 different countries including Vietnam to the East Sea with a water flow of about 500 km^3 yr^{-1} [7]. This abundant surface-water reserve is a favorite resource for aquaculture in the MRD area, most notably is intensive catfish (*Pangasius hypophthalmus*) farming (CF) and wet rice farming.

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In Ho Chi Minh City (HCMC), the average volume of domestic wastewater was about 1,337,000 m^3 d^{-1} in 2018. Binh Hung is the largest capacity domestic wastewater-treatment plant (DWWTP), about 141,000 m^3 d^{-1}. Part of sewage sludge from DWWTPs is for composting, most of the remaining volume is buried in a sanitary landfill.

The potential waste sources for phosphorus (P) recovery, including cattle manure (CM) from cattle farming (CTF), pig manure (PM) from pig farming (PF), sediment from CF, sludges from rubber-latex processing wastewater-treatment plant (RWWTP), and the DWWTPs have not be considered. Assessing the potential waste sources is basis for creating motivation for applied research to effective P recovery in Vietnam. This study includes field surveys, obtained field samples of wastes, as well as data collected from relevant state-management agencies.

2 Methodology

2.1 Survey and data collection

The surveys were focused on gathering information related to the situation, management, and treatment of waste from the studied waste sources, shown in Table 1.

Based on statistical data from GSO, the surveys and sampling areas have been chosen as those places where highly concentrated activities generate waste sources. Table 2 presents the input information from surveys. Sediment samples from catfish ponds were taken in the MRD area, including in An Giang, Dong Thap, and Ben Tre province. Specialized sludge-collection equipment, a Ponar bucket type (model 3-1728-G40, WILCO, USA) was used to obtain sediment from the bottom of catfish pond. At each pond, sediment was taken at 5 points, including the center and 4 points at 4 corners of pond. Samples were mixed to form an average sample.

Table 1 Main input data collected via field survey

Heading	Waste source from		
	Pig and cattle farming	Catfish farming	From WWTPs
Head of pig/cattle/person	x		x
Cleaning method and frequency	x		
Catfish age		x	
Type of feeds/wastewater	x	x	x
Waste collecting method and frequency	x	x	x
Area/yield/capacity	x	x	x
Storage method	x	x	x
Reducing waste volume method	x	x	x
Flow of waste (manure/sediment/sludge)	x	x	x

Table 2 Sampling area according to source of waste

Location (province)	Sample				
	Pig manure	Cattle manure	Catfish sediment	Sludge from RWWTP	Sludge from DWWTP
An Giang			x		
Dong Thap			x		
Ben Tre	x	x	x		
Dong Nai	x			x	
Ho Chi Minh City	x	x			x
Tien Giang	x	x			
Tra Vinh		x			
Binh Duong				x	x
Binh Phuoc				x	
Ba Ria- Vung Tau				x	

PM samples were collected in Dong Nai (DN), Ben Tre, Tien Giang province, and HCMC. CM samples were collected in four provinces that have the largest cattle population including HCMC, Tien Giang, Tra Vinh and Ben Tre province. Sludge samples from RWWTPs were collected in Dong Nai, Binh Phuoc, Binh Duong (BD), and Ba Ria Vung Tau (BRVT) province. There are 2 types of sludge from RWWTP, namely chemical sludge (CheS) and biological sludge (BioS), which originate from the chemical treatment and biological treatment stage, respectively. The surveying and sampling activities were also carried out at DWWTPs. Sludge samples were collected at the 4 most suitable sites in HCMC and Binh Duong. Samples were kept in 20-L-plastic containers with a lid.

The population, rubber production, planting area, number of pigs and cattle data were collected from the GSO [2, 8], the Food and Agriculture Organization [9, 10], MONRE, and Ministry of Agriculture and Rural Development (MARD) of Vietnam [11].

2.2 Analysis method

2.2.1 Chemical analysis

Collected samples were dried at 105 °C to constant mass, then mill into particles size about 500 µm. These prepared sample was digested for multielement analysis. Each 3 gram of sample was weighed and placed in a 250 mL reaction flask. The sample was then moistened with 1 mL of water and slowly added 21 mL of 37% HCl, followed by 7 mL of 65% HNO_3. The sample mixture was then left at room temperature until the foam was gone. In the next step, sample mixture was heated by the heating device, the temperature was raised slowly to reflux conditions and kept stable for 2 h. This digestion method was developed in the European project "Horizontal" [12] with the main goals to create and develop horizontal and harmonized European standards in the field of sludge, soil, and treated biowaste. After cooling at room temperature, the digestion solution was separated by 25 mm syringe filter with pore size 0.45 µm (SYRINGE, FINETECH, Taiwan) before being analyzed. The Al, Fe, Ca, P and the heavy metals (HMs) such as Cr, Cd, Br, Cu, Pb were determined by using an inductively coupled plasma optical emission spectrometer (SPECTRO BLUE TM, SPECTRO, Germany), and Pb also analyzed by energy dispersive X-ray fluorescence spectrometer (EDX- 7000, SHIMADZU, Japan).

2.2.2 Statistical analysis

The coefficient of variation (C_v) was used as an indicator to show the degree of P-reserve distribution of each waste source. The higher coefficient of variation indicates a wider range of variation, meaning that P-reserve is concentrated in some localities. P-reserve (wt%) data by locality and waste source was used as input samples. There are 19 input samples for each waste source by locality, and 95 samples in a total of the studied sources.

2.3 Waste and P-reserve calculation

2.3.1 Calculation of P-reserve in sludge from domestic wastewater-treatment plants

The organic matter, N and P are typical pollutant components of domestic wastewater. Therefore, biological wastewater treatment is the key method applied at DWWTP in the Southern Vietnam. Estimating the amount of sludge generated from DWWTPs focuses on biological tank such as aerotank.

Water supply standards for domestic purposes are regulated according to the Water Supply-Distribution System and Facilities Design Standard TCXDVN 33: 2006 issued by the Ministry of Construction of Vietnam [13]. The water supply level for major city (population more than 1 milion people) is about 200 and 150 L d^{-1} for a person who lives in urban and in rural, respectively. In other provinces and cities, these are about 150 and 100 L d^{-1} for a person who lives in urban and rural, respectively. The generation coefficient (K) is the percentage of water supply converted into wastewater after utilization for living activities. K = 0.8 is specified in the Vietnam standard No.7957 issued in 2008 by Ministry of Science and Technology [14]. Calculating domestic wastewater flowrate is then expressed as

$$Q = \frac{(P_r \times S_r + P_u \times S_u)}{K} \quad (1)$$

where Q is the total domestic wastewater flow rate (L d^{-1}), P_r, P_u (person) and S_r, S_u (L $person^{-1}$ d^{-1}) are the population in rural and urban regions as well as the water supply in both regions, respectively.

The National Technical Regulation on Domestic Wastewater- standard QCVN 14: 2008/BTNMT [15] is required to be met by all the DWWTPs. In which, the content of P in treated wastewater must be less than 6 mg L^{-1} before it is allowed to discharge into the water source used for domestic water supply purposes. P in wastewater is mainly used by microorganisms in biological sludge to form new biomass.

Daily sludge produced is calculated based on following Lam et al. [16] as:

$$P_{TSS}\left(\mathrm{kgTSSd}^{-1}\right) = \frac{Q \times (S_0 - S) \times Y}{1 + (SRT) \times k_d}\frac{1}{0.85} + Q \times (SS_{in} - SS_{out}) \quad (2)$$

where S_0 and S are influent and effluent BOD concentrations in wastewater (kg m^{-3}). SS_{in} and SS_{out} are influent and effluent suspended solids (kg m^{-3}), respectively. The endogenous decay coefficient is k_d (g VSS g VSS d^{-1}), which can be understood as the loss in cell mass because of oxidation of internal storage products for energy and for maintenance and the cell death in biological tank. Biomass yield Y is the ratio of the amount of biomass produced to BOD consumed. The average time of activated sludge in tank is called solids retention time (*SRT*) (d). Factor 0.85 is a typical biomass fraction, which is the biomass VSS to TSS ratio. This factor usually slightly varies in the range of 0.8 to 0.9.

The annual P-reserve in sludge is then calculated using Eq. (3):

$$\dot{m}_{\mathrm{S}}\left(\mathrm{kgd}^{-1}\right) = C_{\mathrm{P,sludge}} \times P_{\mathrm{TSS}} \tag{3}$$

where $C_{\mathrm{P,sludge}}$ is P content in sludge (kg P kg^{-1}).

2.3.2 Calculation of P-reserves in cattle and pig manure

Via this studied result, the excretion from pigs and cattle are collected as wet manure and slurry. According to Cu et al. [17], manure is managed as slurry, liquid and wet manure from in-house separation in Vietnam and also other Asian countries. Most of the surveyed farms do not use bedding in pigpen, which leads to difficulties in cleaning from manure. Pigpen is usually cleaned with an excess of water. Manure from pig and cattle are thus mixed with urine and cleaning water to form slurry.

P-reserves from PF and CTF were calculated as the following formulars:

$$\dot{m}_{\mathrm{P,\,pig}}\left(\mathrm{kgyr}^{-1}\right) = C_{\mathrm{P,pig}} \times \dot{m}_{\mathrm{pig\ manure}} \tag{4}$$

and

$$\dot{m}_{\mathrm{C}}\left(\mathrm{kgyr}^{-1}\right) = C_{\mathrm{P,cattle}} \times \dot{m}_{\mathrm{cattle\ manure}} \tag{5}$$

Where $C_{\mathrm{P,pig}}$ and $C_{\mathrm{P,cattle}}$ are P content in dry PM and CM (kg P kg^{-1}), respectively, and $\dot{m}_{\mathrm{pigmanure}}$ and $\dot{m}_{\mathrm{cattlemanure}}$ are the quantities of dry manure production per year (kg yr^{-1}).

2.3.3 Calculation of P-reserve in sediment from catfish pond

According to Nguyen et al. [18], after three months of catfish culture, the sediment volume is about 1,600 m^3 ha^{-1} and then the sediment volume increase to 1,000 m^3 ha^{-1} month^{-1}. According to surveyed results, each fish growing cycle lasts from 6 to 8 months and 2 to 3 months for cleaning and disinfecting ponds before a new raising cycle. The average yield of catfish production is then about 346 t ha^{-1} yr^{-1}, which is only slightly higher than the average of 300 t ha^{-1} yr^{-1} found by Bosma et al. [19].

The P-reserve is calculated as follows:

$$\dot{m}_{\mathrm{CF}}\left(\mathrm{kgyr}^{-1}\right) = C_{\mathrm{P,catfish}} \times V_{\mathrm{s}} \times R_{\mathrm{s}} \times W_s \times d_{\mathrm{m}} \tag{6}$$

where V_s is the annual volume of sediment at the bottom of a pond (m^3 yr^{-1}). Direct pumped sediment from pond is then dewatered to get wet sediment. R_s is the density of the wet sediment to the direct pumped sediment (m^3 m^{-3}), the W_s (kg m^{-3}) is specific weight of wet sediment, d_m is dry-matter content (kg kg^{-1}), which is the ratio of dried sediment to wet sediment, about 0.25 and $C_{\mathrm{P,catfish}}$ is P content in dry matter of sediment (kg P kg^{-1}).

2.3.4 Calculation of P-reserve in sludge from rubber-latex processing wastewater-treatment plant

Wastewater from rubber processing has a high concentration of nutrient components. Based on the influent and effluent P concentration, the P-reserve from RWWTP is calculated as:

$$\dot{m}_{\mathrm{R}}\left(\mathrm{kgyr}^{-1}\right) = \dot{m}_{\mathrm{rp}} \times 0.9 \times K_{\mathrm{w}} \times (C_0 - C) \tag{7}$$

where $\dot{m}_{\mathrm{rp}}$ is annual rubber production (t yr^{-1}). These data are collected from GSO of Vietnam [2] and the Vietnam rubber association [4]. The coefficient K_w water supply for rubber processing is about 10 m^3 t^{-1} of rubber production. C_0 and C are influent and effluent P concentrations (kg m^{-3}), respectively. Before discharge to environment, outlet wastewater characteristic has to be meet the national technical regulation on waste wastewater, in which the maximum total P concentration in effluent must not exceed 4 mg L^{-1} [20]. In this study, the effluent total P concentration is used for the calculation is thus chosen as 4 mg L^{-1}.

2.4 Cascaded option tree for criteria evaluation

The Cascaded Option Tree (COT) method is used to generate a simple and comprehensible evaluation of the alternatives for P recovery, which was introduced by Bednarz et al. [21]. This method is used for evaluating the different process alternatives based on some chosen relevant criteria. The suitability of each criterion was assessed and indicated in the resulting table by different symbols and colours. In general, the green with a "+" represents the good performance of the option concerning the considered criterion, orange with "0" means acceptable performance, and red with "-" corresponds to unacceptable performances. If an option is especially suitable, this is indicated by "++". The selection of evaluation colour is based on the analysis results of a criterion or a sub-criterion.

For each process option, evaluated criteria are then recorded in columns. In this study, each waste source as an option was evaluated based on 5 critical criteria:

- Total P-reserves from potential sources in Southern Vietnam,
- P, Calcium (Ca), Aluminum (Al) and Iron (Fe) content in waste,
- HM contents in waste,
- Easy of collecting waste from waste sources,
- Ability to transport waste from waste sources.

This study evaluates the potential for P recovery, so the criterion of P-reserve from waste sources is extremely important and needs to be evaluated. In addition, besides the useful elements for fertilizer production from P recovered products such as P, Mg, Ca or K, the undesirable elements such as Fe, Al and HMs [22] from waste sources also need to be considered. P, metal, HM contents affect the selection of P recovery method. In which, P recovery by wet chemical method is as an option that can be prioritized for consideration. The detailed evaluations are the basis for generating the general option tree in the conclusion, as shown in Fig. 8, which indicates the optimal options for P-recovery.

3 Result and discussion

3.1 Criterion: total P-reserves from potential sources in Southern Vietnam

Evaluation of overall P-reserves that can be potentially obtained from different waste sources is an important criterion and needs to be evaluated first. It is the necessary prerequisite to further evaluate the other criteria. The larger the P-reserve is in the waste source, the higher is the attractiveness of that source. However, the selection of the waste source with the highest potential needs to be based on an evaluation of the combination of all criteria.

P-reserves from studied waste sources are shown in Fig. 1. This result serves as a basis for indicating the waste sources leading to the largest P-reserves.

P-reserves from waste sources mostly increase over the years from 2015 to 2018. P-reserve from PF and CF are recorded as the highest group, about 21.7 and 17.7 kt in 2018, respectively. Total P mass in sludges from DWWTPs and RWWTPs is about 5.4 kt yr^{-1}. The amount of P discharged from RWWTP is about 1.6 kt yr^{-1}.

It can be divided into two groups of P-reserves. The first group corresponds to P-reserve above 6 kt yr^{-1}. They include P reserve from PF, CF and CTF. So that, they best fulfill the criterion on the amount of P-reserves for recovery, and colored in green, as shown in Fig. 8. The second group including from rubber and domestic wastewater-treatment plants have acceptable performance with P-reserves below 6 kt yr^{-1}, which may be acceptable for technical reason if they perform well concerning other criteria.

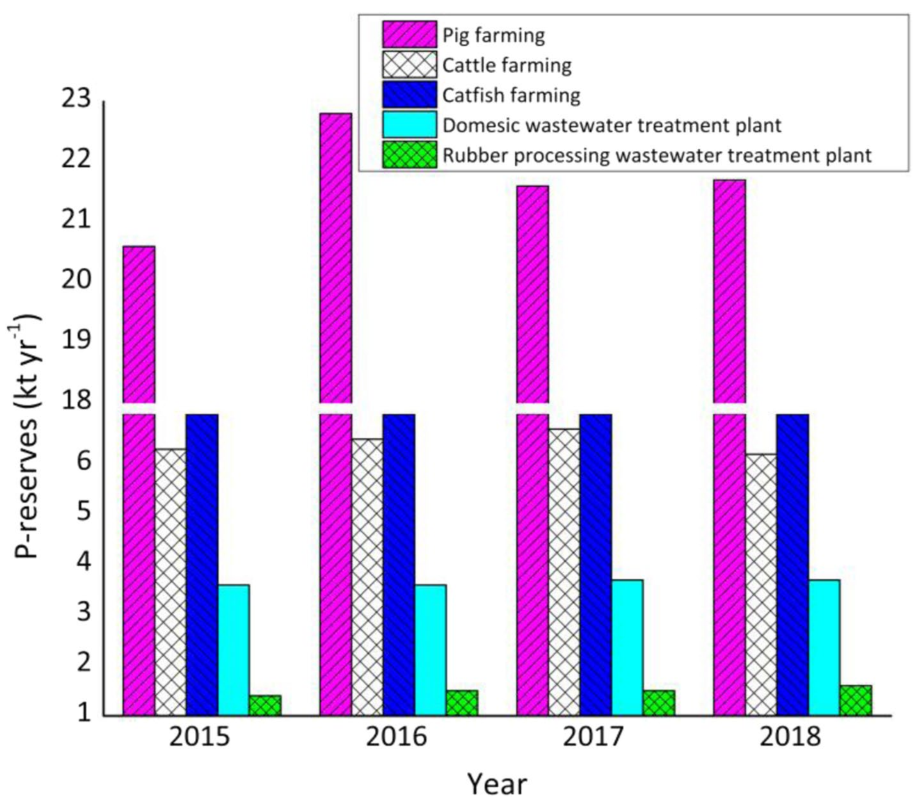

Fig. 1 Estimated P-reserves in studied waste sources

3.2 Criterion: phosphorus, calcium, aluminum and iron content in waste

Metallic compounds are used in some wastewater treatment processes to remove contaminants, which leads to the presence of metals in wastewater sludge, but they are undesirable in a final product of P recovery. The higher concentration of metal impurities in the wastewater sludge, the more process and P recovery operating cost are negatively affected. Figures 2 and 3 show the mass fraction of P, Ca, Al, and Fe in the studied wastes.

The P content in CheS from RWWTPs is 13 times higher than in catfish sediment (CFS). Similarly, if comparing the BioS from RWWTP with sludge from

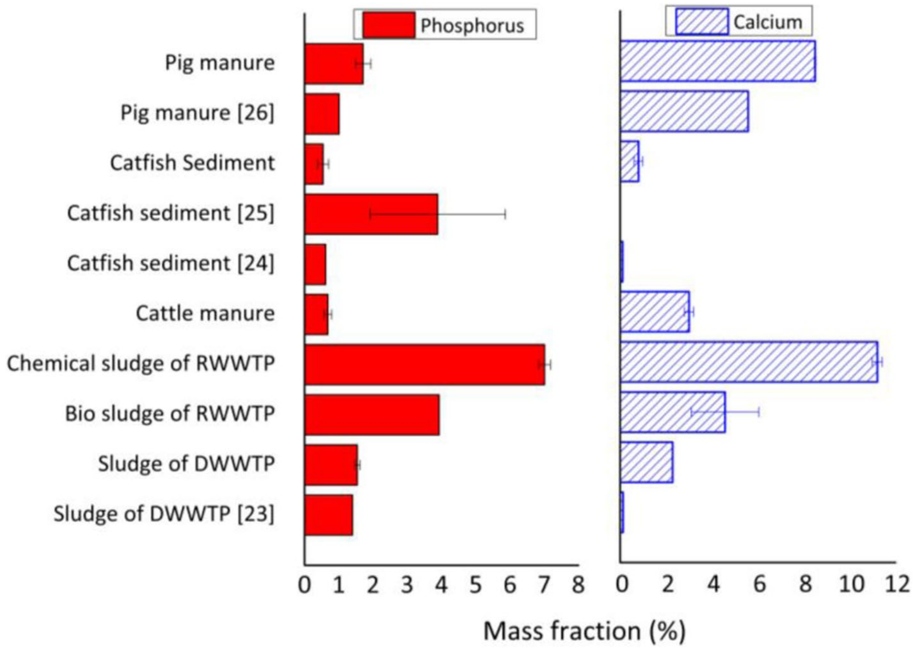

Fig. 2 P and Ca content in wastes

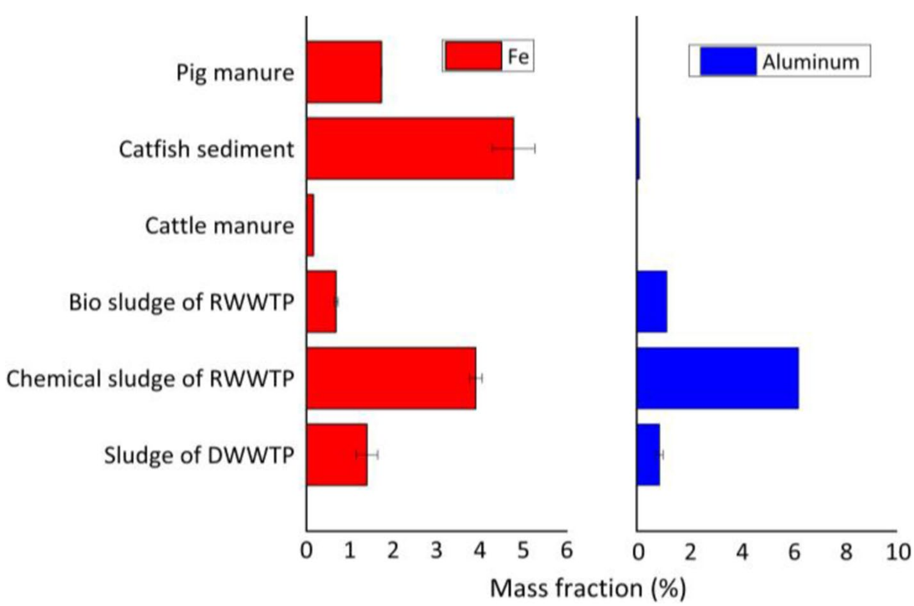

Fig. 3 Fe and Al content in studied wastes

DWWTP, the P contents are 39 ± 1.0 and 15 ± 1.0 g kg^{-1}, respectively. The P concentration in influent rubber wastewater is about 50 times higher than the required standard concentration for discharge to environment. The most RWWTPs have a chemical treatment stage, which combines chemicals like hydrated lime, flocculants such as poly aluminum chloride (PAlC), ferrous sulfate heptahydrate and also polymers to remove P from wastewater.

P content in sludge of DWWTP in this study is quite similar to the results of Alam et al. [23], about 1.5 wt%. According to Truong and Tran [24], P content in catfish sediment is about 0.5 wt%, quite similar to the results of this study. However, the research of Chau et al. [25] shows that the average P content in sediment from catfish ponds is higher, about 3.9 ± 2.0 wt%. Both this study and that of Song et al. recorded that Ca content in PM was above 5 wt%. [26].

The sludge from RWWTPs has the highest Al content of wastes studied. CheS from RWWTPs has Al and Fe contents of up to 6.2 and 3.6 wt%, respectively. Sediment from CF has a high Fe content. The metal to P mass ratios, which characterize purity of final product that can be obtained from the respective source without further treatment, are shown in Table 3. The higher this ratio is, the lower is the degree of purity, which directly affects P-recovery potential.

The highest ratio of Fe to P mass is recorded in CFS, about 8.3. Water exchange in the catfish pond takes place once or twice per day, each time replacing 30 to 100% of the pond water [27]. Freshwater for the exchange is taken directly from the river or canal nearby the farm making it difficult to control Fe concentration. The habit of using hydrated lime to disinfect and stabilize the pH can also cause high Fe content in sediment. The hydrated lime quantity used for CF is about 5.2 to 5.9 kg t^{-1} of fish [19]. The ratios of Ca to P in PM and CM are recorded respectively as 5.0, 4.4, highest in studied wastes. Sludge from DWWTP and CheS have Al content ratios much higher than P about 0.6 and 0.9, respectively. This is the highest ratio group in the studied wastes.

The evaluation result shows that BioS has the best purity of the studied waste group, it is rated as a good performance to be considered for P recovery. CheS, PM, CM, CFS, and sludge from DWWT are found to have higher levels of impurity. They thus are evaluated as having only acceptable performances level, shown as yellow in Fig. 8.

3.3 Criterion: heavy-metal content and related quality standard on fertilizers

HM contents in studied samples and from published studies are shown in Table 4. And the table also includes the HM content limit in fertilizers taken from regulations by the authority in some countries such as MARD of Vietnam, Canadian Council of Ministers of the Environment, The British Standards Institution, the European Commission and standard from Ministry of Agriculture and Rural Affair of China.

Analyzed dried material results show that Cd contents are not detected in most of the samples, while some other studies found rather high contents. E.g. the Cd content in wastewater sludge sample in the study of Ahadi et al. is about 4.7 mg kg^{-1} [28]. The Mercury (Hg) content in all studied samples were not analyzed. The content of Pb in sludge of DWWTP is about 119 mg kg^{-1}, also somewhat lower than in the study by Ahadi et al. [28]. Cu is detected in all studied material samples, the highest value found in PM with 400 mg kg^{-1}, the lowest in CM with 100 mg kg^{-1}. Compared to the results for PM reported by Song et al. [26], the Cu content in this study is roughly 2.5 lower. Dry CM appears to be the cleanest of investigated wastes, for which none of the HM as Cd, Cr, and Pb could be detected. The HM contents in PM and CFS are lower than the standard of fertilizer quality in Vietnam. The result in Table 4 shows that HM contents in DWWTP are much higher than found in other studied wastes. Especially, the content of Cr, Cu, and Pb in sludge of DWWTP are highest. BioS and CheS from RWWTP show a large difference in HM content. For example, Cr content ratio in CheS to BioS is high, about 12, which suggests that the HMs are introduced with chemicals such as PAlCs and hydrated lime added during treatment.

Table 3 Metal to P mass ratio in studied wastes

Mass ratio (mg mg^{-1})	Waste					
	Pig manure	Catfish sediment	Cattle manure	Sludge of DWWTP	Bio-sludge of RWWTP	Che-sludge of RWWTP
Fe to P	1.01	8.27	0.24	0.9	0.17	0.55
Al to P	0	0.18	0	0.57	0.29	0.88
Ca to P	4.97	1.48	4.41	1.48	1.16	1.6

Table 4 Heavy metal contents in mg kg^{-1}

Material	Cd	Pb	Cr	Hg	Cu
Pig manure	BDL	74 ± 2	84 ± 5	NA	400 ± 50
Catfish sediment	BDL	41	89 ± 6	NA	120 ± 10
Cattle manure	BDL	BDL	BDL	NA	100 ± 10
Sludge of DWWTP	BDL	119 ± 14	582 ± 265	NA	440 ± 30
Bio-sludge of RWWTP	BDL	BDL	14 ± 5	NA	130 ± 60
Che-sludge of RWWTP	1	34	167 ± 15	NA	143 ± 10
Sewage Sludge [28]	5 ± 1	133 ± 14			121 ± 16
Catfish sediment [24]	0.02 ± 0.003	0.03 ± 0.01	59 ± 18		2.54 ± 1
Cattle manure [29]	0.1	2	1.4		16.4
Pig manure [26]	0.3 ± 0.07	9 ± 2	22 ± 1		986 ± 69
Vietnam Technical Regulation on Fertilizer Quality [30]	< 5	< 200		< 2	
Chinese Standard of Organic Fertilizer [31]	3	50	150	2	
British Specification for Composted Materials [32]	1.5	200	100	1	200
Canadian Standard of Compost Quality- Category A [33]	3	150	210	0.8	400
Canadian Standard of Compost Quality- Category B [33]	20	500	1060	5	757
European regulation on fertilising products [34]	1.5	120	100		300

BDL below to the detection level, *NA* not analyzed

Compared to regulations on HM content limits for fertilizers in many countries and regions, some studied wastes can meet some standards. For example, all studied wastes contain fewer HM contents than required by the Canadian Standard of Compost Quality [34], including Cd, Pb, Cr, Cu, and Br. Vietnam standards_ QCVN 01-189:2019/BNNPTNT – National Technical Regulations on Quality Fertilizers does not mention any limits for Cr, Cu, and Br. HMs including, Cd, Pb have lower contents than the Vietnamese standards in all wastes [30]. PM, CFS, and CM also meet the British Specification for Composted Materials [32].

It is clear that, the more HM contents in the waste is, the lower attractiveness of P recovery is. HM contents in CFS, CM, PM and sludge of RWWTPs are lower than the limit requirements in most standards of fertilizers. This is a very positive signal and suitable for P recovery application. The highest Cr and Pb contents are detected in sludge of DWWTP, so it is assessed as an acceptable performance only, colored as yellow in the general COT, shown in Fig. 8.

3.4 Criterion: ease of collecting the waste from waste sources

3.4.1 Sub-criterion: accessibility to waste sources

Waste collection activities can be the cause of increasing the risk of disease spreading on farming between areas. Pig, cattle, and catfish are very sensitive to animal diseases. The hemorrhage disease is the main cause of major losses in CF in MRD. This disease is mainly caused by *Aeromonas hydrophila* and *Edwardsiella ictalurid* [35]. These bacteria quickly spread through water, sediment, or unconsumed food and can cause the death of up to 80% of infected catfish [35–37].

African swine fever (ASF) is a devastating disease of swine and the pig industry [38]. ASF is characteristic of a hemorrhagic phenomenon and suppresses the immune system in pigs [39, 40]. Highly virulent strains of the virus that cause acute illness can lead to a mortality rate close to 100% within 4 to 15 days of infection [41]. In February 2019, the ASF appeared first in Hung Yen, Vietnam and then spread to 62 provinces through July 2019. The number of infected pigs to be killed was about 5.7 million after 8 months disease outbreak [11].

These pathogens from CF, CTF and PF are easily spread through many different infectious pathways, of which waste collection and transport are also great risk of spreading. Therefore, the attractiveness for P recovery from these wastes is very low even if completed meeting the required compliance to prevent disease transmission. In the opposite, accessing the wastewater treatment plants for sludge collecting and transporting is convenient and simple, and indicated in green on criterion evaluation, shown in Fig. 8.

3.4.2 Sub-criterion: P-reserves distribution

The distribution of P-reserves by geographical location is considered as a factor affecting the collection capacity and recovery potential. The P-reserve distribution in percentage by weight (wt%) for each waste source by location is shown in Fig. 4. Numerically, the distribution of P-reserve is evaluated by determining the coefficient of

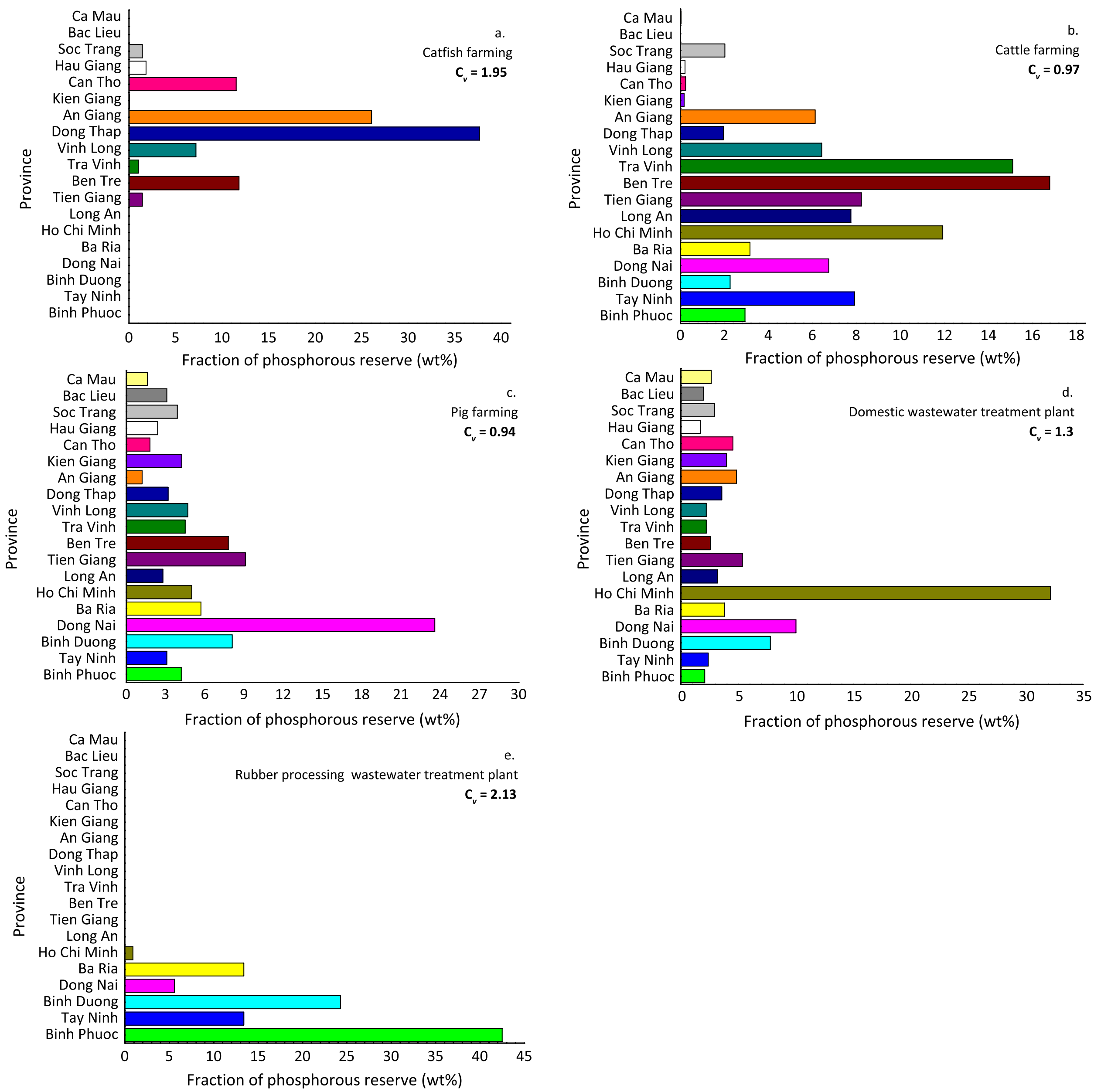

Fig. 4 P-reserve distribution in wt% by province

variation shown in Fig. 4. The smaller value of C_v is, the more non-concentrated distribution of P-reserve is.

The P-reserve from CF concentrates in 4 provinces. Dong Thap has the highest P-reserve, about 38% of the total mass in the studied regions, shown as Fig. 4a. The C_v of CF is calculated about 1.9, higher than in comparison with PF and CTF. Figure 4b and c show that P-reserves from PF and CTF are widely and evenly distributed among localities, one of the reasons is the spontaneous and small-scale development of livestock industry in Southern Vietnam.

P-reserve from DWWTPs in HCMC is the highest, about 32 wt%. According to MONRE's report, most domestic wastewater in MRD has not been collected and treated [1]. HCMC has the highest rate of collection and treatment in the region, which only reaches 21.2% [1]. By June 2021, there were 5, 6 and 13 DWWTPs with a capacity above 10,000 $m^3\ d^{-1}$ in HCMC, other provinces in SE area and MRD region, respectively. Overall, the coefficient of variation value in P-reserve from domestic wastewater is median in comparison with other waste sources, about 1.3.

P-reserve from RWWTPs is concentrated only in the SE area, especially in Binh Phuoc. Thus, the C_v from RWWTPs is recorded the highest in comparison with other studied waste sources.

P-reserves from PF and CTF are spread throughout all provinces. These two waste sources are thus only rated as acceptable with respect to P distribution. P-reserve from DWWTPs is fairly distributed throughout all provinces, except for HCMC. However, DWWTPs are usually designed with a very large capacity, so the volume of wastewater sludge is high enough to set up its P recovery unit at the discharge site. This waste source also has its attractions and advantages and rated at good performance. P-reserve from CF and RWWTP are concentrated in few localities. The collection processes for these waste sources are thus very convenient. Their performance levels are rated as good.

Summarizing all sub-criteria, wastes from DWWTPs and RWWTPs meet a good performance and are thus colored in green only as shown in Fig. 8. The remaining waste sources can only meet one of the sub-criteria, thus showing only acceptable performance.

3.5 Criterion: ability to transport waste from waste sources

There are two factors, which directly affect the ability to transport the waste, namely the geographic distance between main disposal sites and the character of the waste. The geographic distance directly affects the length of waste collection routes and thus also the transportation costs. The character of the wastes, or called physical forms of waste, e.g., if it is obtained as liquid or solid affects the mode of transportation and storage. In addition, the topographical condition is also a factor to be considered.

3.5.1 Sub-criterion: Geographic distance and topographical conditions

A group of the highest P-reserves by province was formed for each waste source. This group constitutes waste (as raw-material) supply network for a central P-recovery unit located in one of the provinces within each group. Table 5 shows the potential groups with the highest P-reserves by waste source.

The locality with the largest P-reserve in each potential waste source will be selected to install the central P-recovery plant. The collecting and transporting route of waste sources for each potential group has been established based on the global positioning system device GARMIN GPS MAP 78 S. The distance of the transportation routes of waste is shown in Fig. 5.

The group of longest transportation routes of PM and sludge from RWWTP are recorded, approximately 450 and 240 km, respectively. However, P can be recovered at each RWWTP by its P-recovery unit. Therefore, the length of the sludge transport route is not really important for this waste source.

Two major modes of transportation can be considered for the transport of wastes, namely land and inland-waterway transport.

The network of rivers and canals in MRD is dense as shown in Fig. 6, while land-transport infrastructure is not developed. Catfish ponds are often located near water sources such as rivers and canals. Thus, sediment transporting by inland waterway is suitable in the MRD region.

P from DWWTP and RWWTP can be recovered at the discharge site by its P-recovery unit. Therefore, they are assessed as showing good performance. The shortest waste transportation route belonged to CTF, and thus it is rated as good performance. The difficulty with unfocused P-reserve distribution and long transportation routes are major hindrances to P-recovery from PF, thus only ranked to an acceptable performance rating. CF is evaluated as good performance due to the convenient and short collection route.

Table 5 Group of highest P-reserves by province and waste source

	Group of provinces with the highest P-reserves for each waste source				
	Pig manure	**Cattle manure**	**Catfish sediment**	**RWWTP**	**DWWTP**
Location (province)	1. Dong Nai	1. Ben Tre	1. Dong Thap	1. Binh Phuoc	1. HCMC
	2. Tien Giang	2. Tra Vinh	2. An Giang	2. Binh Duong	2. Dong Nai
	3. Binh Duong	3. HCMC	3. Ben Tre	3. BRVT	3. Binh Duong
	4. Ben Tre	4. Tien Giang	4. Can Tho	4. Tay Ninh	4. Tien Giang
∑P-reserve,%	49	52	87	94	55

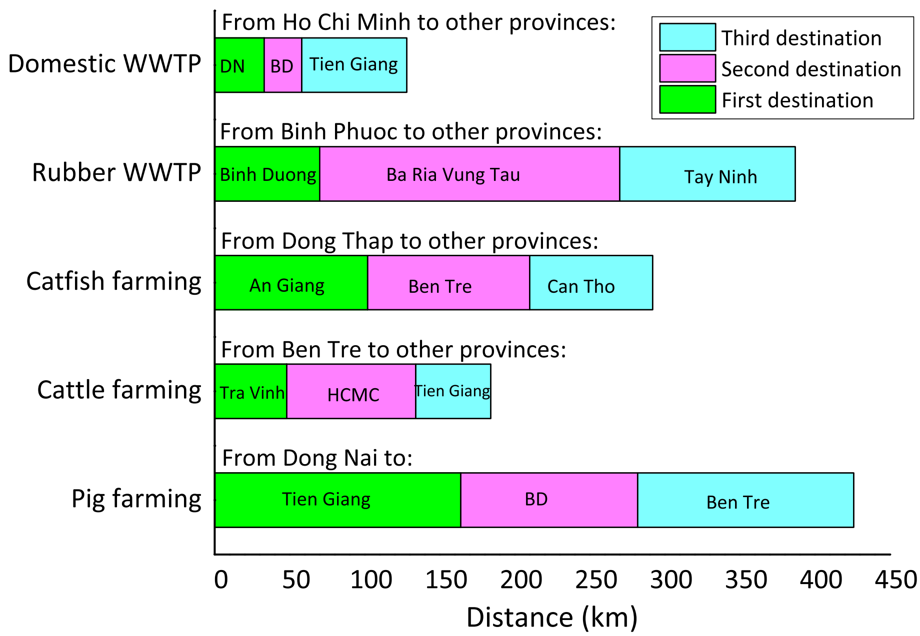

Fig. 5 Collection route of highest 5 potential waste sources group

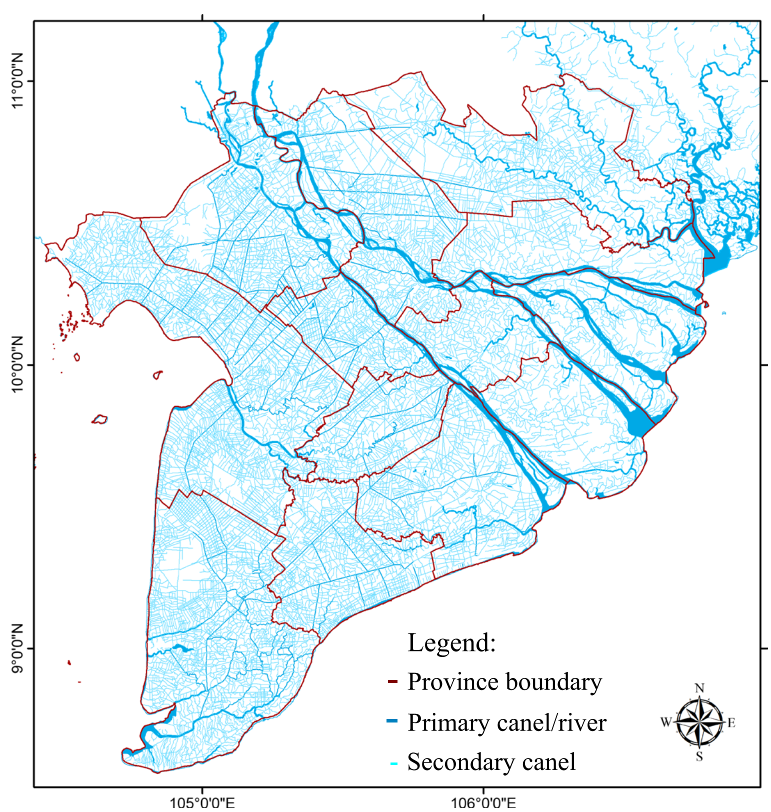

Fig. 6 River system and cannel networks in MRD

3.5.2 Sub-criterion: physical forms of waste

According to The No. 38/2015/NĐ-CP: Decree on the Management of Wastes and Scraps [42], it must be guaranteed that no waste, dust, odor, and water leakage are dropped or produced during the transporting. The physical form of waste thus affects the effort to meet these requirements. The current situation of waste physical forms is shown in Fig. 7. The diagram also reflects the degree of waste management and treatment for each waste source. The red dashed line divides graphics into two parts, where on the left side the status of waste production and treatment are shown. On the right side, the options should be implemented before the waste can be collected and transported are shown.

Waste from CTF and PF consists of a mixture of slurry and wet manure, which thus requires additional effort for dewatering and separation.

Sediment from CF consists mainly of superfluous food and fish excretion [19]. The sediment consists of a high fraction of water after being pumped, thus an additional step of dewatering is required.

The situations of wastes from RWWTPs and DWWTPs are shown in Table 6. Most wastewater treatment plants have a dewatering stage.

In particular, the sludges from RWWTPs and DWWTPs are already dewatered, it is convenient for transportation, so both sources are rated as good performance. Waste from the other sources including PM, CM and sediment from CF have the high-water content that

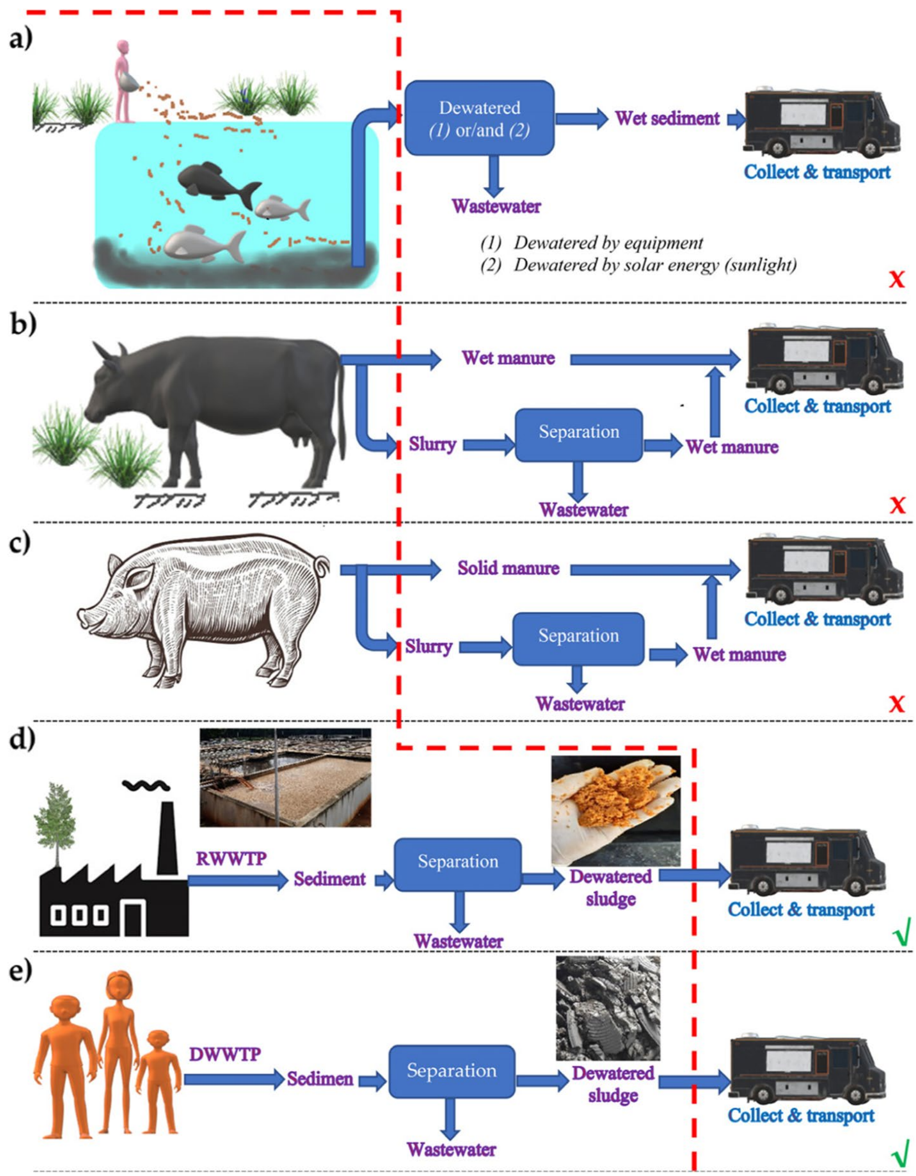

Fig. 7 Schematic representation of waste production, current treatment, and transport options

Table 6 Sludge type and dewatering method at RWWTP and DWWTP via survey data

Enterprise	Wastewater	Sludge	Dewatered by	
			Machine	Natural drying
Ben Suc Rubber Corporation	Rubber	Both(*)	Yes	No
An Lap Rubber Corporation	Rubber	Both(*)	Yes	No
Xuan Lap Rubber Corporation	Rubber	Both(*)	Yes	No
Cam My Rubber Corporation	Rubber	Both(*)	Yes	No
Hang Gon Rubber Corporation	Rubber	Both(*)	Yes	No
Ba Ria Rubber Corporation	Rubber	Both(*)	Yes	No
Loc Ninh Rubber Corporation	Rubber	MixS(*)	Yes	No
Binh Phuoc Rubber Corporation	Rubber	MixS(*)	Yes	No
Binh Hung plant	Domestic	BioS	Yes	No
Tham Luong plant	Domestic	BioS	Yes	No
Binh Hung Hoa plant	Domestic	BioS	No	No
Di An plant	Domestic	BioS	Yes	No

MixS(*): CheS and BioS are mixed before dewatering

Both(*): CheS and BioS

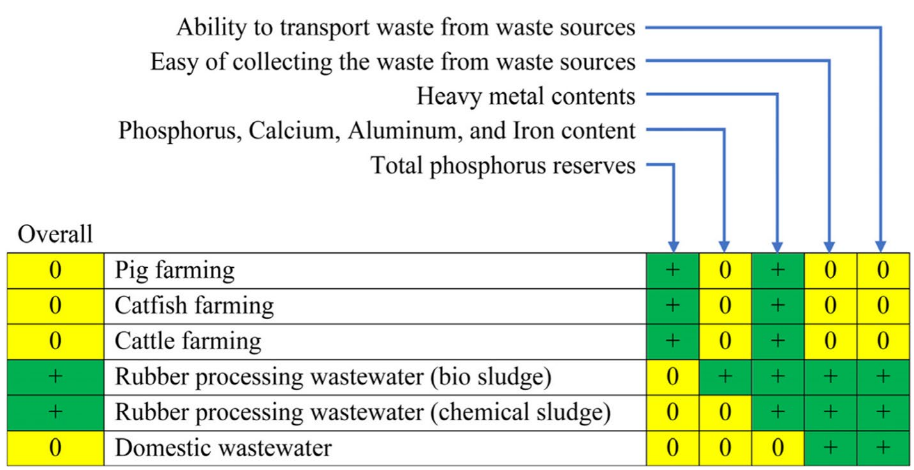

Fig. 8 General cascade option tree for potential waste resources is established

need extra treatment so that these sources have only an acceptable performance.

Sludges from DWWTP and RWWTP meet all sub-criteria leading to be a good rating colored in green, shown in the Fig. 8. The other waste sources only meet one or no sub-criterion, so they are evaluated as acceptable performance.

The evaluation results of criteria for waste sources to P-recovery in Southern Vietnam are shown in Fig. 8. The overall evaluation is shown in the leftmost column. The general performance evaluation is set to good if the majority of criteria was evaluated as good and colored as green as Fig. 8. Sludge from RWWTPs met good performance for almost considered criteria. Even though sludge from DWWTPs was scored worse, the recovery of P on their sites may still be attractive due to the concentrated large amounts that may lead to decentralized P-recovery plants. The unfavorable conditions for collection, transportation and low P content reduce the attractiveness of wastes from CF, CTF, and PF.

4 Conclusion

The main objective of this study is to evaluate the potential of P recovery from five waste sources in Southern Vietnam. The criteria selected to be used as a basis for assessing include both internal and external issues of the waste sources. The COT method gives an overview of how well the criteria are met with the potential to recover P. Comparing all waste sources regarded, the wastewater sludge from RWWTPs has the highest potential for P-recovery. The wastewater sludge from RWWTP can quickly be used as the most suitable input material in the P recovery process in Vietnam.

In the future, if all P-reserves from studied waste sources are recovered, it could solve about 16% of the nutrient P quantity as fertilizers for agricultural used in Vietnam in 2019.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s42834-023-00169-8.

Additional file 1: Table S1. Input parameter values utilized for the calculation of P reserves in the studied wastesources.

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Authors' contributions

Khang Vu Dinh conceptualized the study and conducted experiments. Le Hung Anh supported the implementation of ideas through technical issues and equipment for analysis and survey. Andreas Pfennig provided ideas, commented and reviewed on editing the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

All data generated or analyzed during this study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare they have no competing interests.

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