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Advanced research on piggery wastewater resource recovery and utilization

Mei Tao[a,b,c], Houzhen Zhou[a,b], Yangwu Chen[a,b], Yulong He[c], Shiyang Dong[a,b], Chen Wang[a,b], Zhouliang Tan[a,b,*]

[a]*Key Laboratory of Environmental and Applied Microbiology, Chengdu Institute of Biology, Chinese Academy of Sciences, 610041 Chengdu, email: china tanzhl@cib.ac.cn (Z. Tan)*
[b]*Environmental Microbiology Key Laboratory of Sichuan Province, Chengdu Institute of Biology, Chinese Academy of Sciences, 610041 Chengdu, China*
[c]*Southwest Jiaotong University, 611756 Chengdu, China*

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ABSTRACT

Piggery wastewater is one of the most common wastewaters produced throughout the world. The large volume and concerning qualities (high concentrations of organic matter, suspended solids, ammonia nitrogen, and phosphorus) make it one of the largest sources of pollution. Meanwhile, most of the pollutants in piggery wastewater are highly nutritious, thus possessing great potential and significance for recycling. Therefore, the main focus falls on the recovery and utilization of resources from piggery wastewater. In this review, the characteristics and hazards of piggery wastewater were discussed. In addition, the treatment and utilization methods were reviewed, including fertilization, energy utilization, and base material utilization. Future prospects for utilization as resources were also explored in this work.

Keywords: Piggery wastewater; Anaerobic treatment; Resource utilization; Energy; Fertilization

1. Introduction

With the large-scale development of pig breeding and production industry, a great amount of piggery wastewater is generated every year and has become one of the most highly produced wastewaters throughout the world [1]. This is particularly true for Asian countries, such as China and South Korea. China is the largest pork producer in the world and possesses a national stock of around 500 million pigs, which results in the generation of more than 6.6×10^8 tons of piggery wastewater per year. The discharged wastewater contains at least 2.7×10^7 tons of chemical oxygen demand (COD), 1.35×10^7 tons of total nitrogen (TN), and 1.44×10^6 tons of total phosphorus (TP) [2]. According to the first national census on pollution sources, COD in piggery wastewater was about 8.5 million tons, accounting for 30% of the total emissions, while nitrogen and phosphorus accounted for 30% and 40% of the total emissions, respectively. Moreover, large quantities of untreated piggery wastewater are discharged from scattered household pig farms directly into the environment due to poor management and insufficient sewage facilities.

Piggery wastewater is a mixture of pig urine and feces with flushing water and has high organic loading and nutrient content. It also contains large number of toxic and harmful pollutants as well as pathogenic bacteria. Some emerging contaminants, such as antibiotics, are also detected in piggery wastewater. Therefore, if the piggery wastewater is discharged directly into the aquatic environment or used for farmland irrigation untreated, the pollutants and pathogenic bacteria contained in piggery wastewater would accumulate in soil and groundwater, and result in severe environmental pollution and ecological impacts [3].

Current piggery wastewater treatment modes can be broadly divided into three types, namely the returning

* Corresponding author.

farmland mode, the natural treatment mode, and the factory treatment mode. Anaerobic digestion has been recommended as the primary treatment process for piggery wastewater due to its lower energy consumption and low operating cost. In addition, methane can be produced during the process and utilized as an energy resource during the digestion process. Some anaerobic digestion processes, such as upflow anaerobic sludge bed or upflow anaerobic sludge blanket (UASB) [4], anaerobic filter, internal circulation, and anaerobic baffled reactor have been widely used for this purpose. Aerobic processing, for example, in a sequencing batch reactor (SBR) [5], is another common way of processing piggery wastewater. In order to obtain a better processing efficiency, various methods integrating anaerobic and aerobic treatment processes have been proposed. The application of mixed processing mode UASB and SBR is one such example [6].

On the other hand, the organics in piggery wastewater are a kind of biomass, which make an ideal renewable resource. If used reasonably, piggery wastewater can be converted into energy and fertilizer. Wise choices in this regard could bring about positive outcomes for industrial development, environmental protection, and efficient resource utilization. Therefore, the development of a technology for efficient resource utilization has become particularly important and inevitable for piggery wastewater treatment. In this review, the research progress on the utilization of resources present in piggery wastewater is discussed in detail, thus providing some references for further study of piggery wastewater treatment and resource utilization.

2. Characteristics of piggery wastewater

Abundant discharge and high pollutant concentrations are the two most obvious characteristics of piggery wastewater.

2.1. Abundant discharge

One pig excretes 5.4 kg manure per day. Taking the flushing water into consideration, the wastewater discharge for one pig turn out to be ca. 30 kg per day, which adds up to 11 tons per year. The pollution load of an industrialized pig production line with 35,000 heads is comparable to the pollution load of a town with a population of 100,000 people [7,8]. In addition, 650 million pigs can discharge as much COD as 2 billion people in the environment each year [9].

2.2. High pollutant concentrations

In general, piggery wastewater is characterized as having high concentrations of COD, biological oxygen demand (BOD), and suspended solids. It is easy for biodegradation, although the quality of piggery wastewater is greatly affected by the pig production stages and the methods their manure is collected [10]. Climate and seasonal variations can also affect the wastewater quality and quantity. In this review, the piggery wastewater qualities of different countries and regions are comprehensively summarized and presented in Table 1 [4].

The results presented in Table 1 show that the piggery wastewater contains abundant nutrients (TP and TN), which make it a good nutrient resource and fertilizer. Due to this reason, the mass discharge of such a highly concentrated organic wastewater will not only result in serious pollution, but will also cause wasting of a major resource. Therefore, the main focus falls on finding applicable methods to retrieve and utilize potential resources present in piggery wastewater.

3. Resource utilization

3.1. Energy utilization

3.1.1. Biogas

The technology to obtain biogas from wastewater treatment has been widely used for decades throughout the world. Piggery wastewater is an ideal raw material for biogas production because of its high buffering capacity, high nitrogen content, and wide range of nutrients (which are needed by methanogens) [18]. Biogas fermentation of piggery

Table 1
Characteristics of piggery wastewater (mg/L)

COD	NH_3–N	BOD	TP	TS	VS	TN	Reference
1,500–2,600	550–850	\	40–70	\	\	700–900	[6]
8,929–13,819	1,490–1,870	\	\	9,840–16,070	4,530–7,160	1,852–2,103	[11]
3,750	1,761	\	\	4,188	2,112	\	[12]
3,500–5,200	620–940	1,700–2,600	\	\	\	\	[4]
524–18,479	22.2–1,598		10.7–230			116–2,288	[13]
1,640.63–5,039.06	168.45–822.80	1,076.74–2,621.33	22.17–188.25	786.00–2,654.00	\	376.50–952.04	[14]
37,643	\	\	620	\	\	2,055	[15]
11,520–16,840	\	7,280–9,690	\	\	\	\	[16]
6,630–53,500	481–1,250	\	254–1,570	4,400–38,700	\	1,024–2,522	[17]
1,915–6,170	338–545	\	26.2–81.6	\	\	365–556	[a]
2,750–4,846	944–2,423	\	27.4–219	\	\	1,371–2,830	[b]
1,168–4,662	1,168–1,486	\	54–250	\	\	1,397–1,634	[c]

[a,b,c]These data were measured at the pig farms located in Zhejiang province, Sichuan province, and Chongqing region of China, respectively, and have not been published yet.

wastewater is considered the most effective means of piggery wastewater treatment for its advantages of energy recovery and resource utilization of biogas residues [19]. Firstly, the organic compounds in piggery wastewater are decomposed into simple structures, and then, under the action of methane bacteria, these simple compounds are converted into biogas. The generated biogas consists mainly of methane (CH_4) and carbon dioxide (CO_2), and it is a clean renewable energy. Furthermore, the biogas residues can also be used in various ways, such as fertilizer, seed soaking, and feed additive. Some European countries have taken the lead in biogas engineering technology and related policy aspects, and these biogas projects have harbored significant economic, environmental, and energy benefits [20]. For example, Poland and Ukraine have long-term perspectives in introducing the biogas projects [21].

Usually, in anaerobic digestion applications, piggery wastewater is co-digested with some other substrate, such as rice straw [18], food waste [22], or some other agricultural substrates [23]. A more detailed review of the process is presented in Table 2.

It can be seen that the co-digestion of piggery wastewater with various carbon-rich substrates showed good digestion performance. The co-digestion of piggery wastewater with easily biodegradable waste appears as a promising technology. In this regard, the mesophilic digestion is the most popular approach. Among the farm biogas projects in Germany and Austria, 90% have adopted mesophilic digestion, while 9% of the biogas projects in Germany and 3% of the biogas projects in Austria have adopted thermophilic fermentation [20]. In addition, in rural China, various eco-agricultural models have been built around biogas systems, such as the pig-biogas-vegetables model, pig-biogas-crops model [19], and pig-biogas-fish system [26].

Even with this level of activity, biogas development is still facing certain issues, including high concentration of effluent organic matter, long fermentation time, and immature supplemental technology. In addition, the fermentation process is strongly affected by temperature and climate. Therefore, the overall process still needs further exploration and improvement [27].

Table 2
Sampled literature works on anaerobic co-digestion

Substrates	Reactor	Operation parameters	Results	Reference
Rice straw + piggery wastewater	Two pilot-scale (1 m^3) digesters	pH: 7.0–8.1 Temperature: 35-40°C	Total biogas production was 22,859 L in Digester A and 1,420 L from Digester B, and specific methane yields of 231 and 12 L CH_4/kg volatile solids (VS) added was achieved, respectively.	[18]
Rice straw + piggery wastewater	A farm-scale digester consisting of two anaerobic cells with the total storage capacity of approximately 13,000 m^3	pH: 6.6–7.8 Temperature: 35°C–40°C	Cumulative energy production of 295 MWh and an estimated specific methane yield of 181 L CH_4/kg VS added were achieved.	[24]
Food waste + piggery wastewater	A semi-continuous anaerobic digester	pH: 7.37 HRT: 20 d Temperature: 37°C	A high methane yield of 0.396 m^3/kg VS added and 75.6% of VS destruction with no significant accumulation of volatile fatty acids was achieved.	[22]
Sugar beet byproduct + pig manure	A semi-continuous stirred tank reactor	HRT: 6 d Mesophilic conditions	Highest system efficiency was achieved at the organic loading rates of 11.2 g $VS/L_{reactor}$·d with the methane production rate and volatile solids (VS) reduction of 2.91 L $CH_4/L_{reactor}$·d and 57.5%, respectively.	[23]
Tomato + pig slurry	A 120 mL glass bottle	Temperature: 35°C	Average final biochemical methane potential (BMP) (100 d) was equal to 276.9 ± 37.74 mL CH_4/g VS added.	[25]
Pepper + pig slurry	A 120 mL glass bottle	Temperature: 35°C	Average final BMP (100 d) was equal to 279.8 ± 42.26 mL CH_4/g VS added.	[25]
Peach + pig slurry	A 120 mL glass bottle	Temperature: 35°C	Average final BMP (100 d) was equal to 261.1 ± 30.39 mL CH_4/g VS added.	[25]
Persimmon + pig slurry	A 120 mL glass bottle	Temperature: 35°C	Average final BMP (100 d) was equal to 241.8 ± 18.52 mL CH_4/g VS added.	[25]

3.1.2. Biodiesel production using cultivation of energy microalgae

Microalgae have been considered as a third-generation biofuel feedstock, and this is not only because of their CO_2 fixation ability, but also because of their capability of producing biomass and lipids [28]. Microalgae can grow extremely rapidly and are rich in oils. The content of oil in microalgae is up to 80%, with the average of 20%–50%. In addition, using microalgae to produce lipids is not subject to seasonal and land restrictions [29]. Usually, microalgae are cultivated in photo-bioreactors or open pond culture systems. After cultivation, the microalgae are harvested from the culture system using centrifugation and filtration. The oil is then extracted from microalgae using squeezing and organic solvent extraction, and finally converted to biodiesel through esterification or transesterification. High concentrations of COD and NH_3–N in piggery wastewater make it a suitable nutrient source for microalgae cultivation. Therefore, the use of microalgae for piggery wastewater treatment is considered as a promising method for recovery of nutrients.

Various microalgae, including *Chlorella vulgaris* and *Chlorella zofingiensis*, have different capacities for producing lipids. In most of the previous studies, COD/nutrient removal and lipid production can be achieved simultaneously using microalgae cultivation in piggery wastewater [1,30,31]. Some researchers have analyzed the effect of removal efficiency of different wastewater disinfection methods on the nutrient removal efficiency and lipid yield, such as, ozonation, autoclaving, and use of NaClO [30]. The effect of wastewater dilution ratio on the removal of nutrients and production of lipids has also been widely studied [31–33]. A short review of such works is presented in Table 3.

According to previous studies (Table 3), using piggery wastewater for microalgae cultivation can reduce the cost of biodiesel production compared with other sources. In addition to the reduction in cost, water purification and biofuel production can simultaneously be achieved, thus bringing along promising economic and environmental benefits.

3.1.3. Microbial fuel cells

The microbial fuel cell (MFC) is a novel renewable energy technology, which can directly generate electrical current. In this technology, microorganisms serve as biocatalysts for the oxidation of organic compounds, during which, chemical energy is converted to electrical energy. Piggery wastewater contains large amounts of organic compounds, making it a potential substrate for MFCs [37]. Recently, many studies concerning MFCs have been conducted, and details of these are summarized in Table 4 [38].

The results presented in Table 4 show that MFCs can remove nutrients from piggery wastewater and simultaneously generate electricity. This is a new type of technology for resource utilization and has promising prospects for development. However, this new technology is still facing some challenges, such as low-power densities and low treatment capacity, which currently limit its feasibility for practical applications. At present, MFCs are still in their experimental stage.

3.2. Fertilization

3.2.1. Nitrogen and phosphorus recovery

For the recovery of nitrogen and phosphorus, various physical and chemical methods have been reported. These methods include metal ion (Al, Fe, and Ca) precipitation [43], adsorption [44], and struvite (magnesium ammonium phosphate [MAP]) crystallization [45]. At present, the most common research and application is focused on struvite crystallization. Struvite (MAP; $MgNH_4PO_4{\cdot}6H_2O$) precipitation has been widely used in the treatment of piggery wastewater due to its ability to simultaneously remove and recover P and N from wastewater. In addition, compared with other phosphorus recovery products, the phosphorus content obtained from struvite precipitation is up to 51.8%, while the phosphorus content of the highest grade phosphorus ore in the world is just about 46% [46]. In addition, in comparison to the P-rock products, the slow nutrient leaching loss, low frequency of application, and low heavy metal content make struvite an ecofriendly fertilizer [47]. Struvite precipitation occurs when PO_4^{3-}, NH_4^+, and Mg^{2+} are at equimolecular concentration under slightly alkaline conditions (Reaction Eqn. (1)).

$$Mg^{2+} + NH_4^+ + HPO_4^{2-} + OH^- + 5H_2O \rightarrow MgNH_4PO_4{\cdot}6H_2O \quad (1)$$

Apart from significant amount of phosphorus and nitrogen, piggery wastewater also contains certain amount of Mg^{2+}. Once the pH of piggery wastewater increases to an appropriate value, PO_4^{3-}, Mg^{2+}, and NH_4^+ crystallize to form struvite [48].

The recovery efficiency of nitrogen and phosphate along with the purity of struvite mainly depends on the pH of wastewater and the molar ratio of Mg^{2+}, NH_4^+, and PO_4^{3-} [49]. Huang et al. [50] have studied the recovery of nutrients from swine wastewater using special devices, which can be simultaneously used for the treatment of wastewater and for struvite decomposition. Song et al. [51] demonstrated the feasibility of nutrient removal and recovery from anaerobically digested swine wastewater using struvite crystallization without chemical addition and discussed its effect on the removal performance. The obtained optimal conditions and removal performances are summarized in Table 5.

3.2.2. Organic fertilizer

Piggery wastewater is commonly used as a land fertilizer, serving as a significant source of nutrients in many European countries [3]. In many rural areas in China, piggery wastewater is directly used for land irrigation. Composting is another simple and effective method to realize the disposal and resource utilization of piggery wastewater. Complex organic nutrients can be decomposed into soluble nutrients and humus through the metabolism of various microorganisms. Meanwhile, the high temperature generated by accumulation (60°C–70°C) can kill bacteria, parasites, and weed seeds in the raw material. Therefore, harmless treatment of piggery wastewater can be achieved using this method.

In large-scale pig farms, piggery wastewater is usually subjected to anaerobic fermentation. The remaining biogas

Table 3
Lipid production capacity of different microalgae cultured with piggery wastewater

Microalgae species	Substrates	Culture conditions	Results	Reference
Scenedesmus obliquus YSW-14	A 40% concentration of piggery wastewater effluent	Light intensity: 45–50 μmol/(m^2·s) Temperature: 25°C Time: 40 d	The microalgae grown in a 40% concentration of piggery wastewater effluent showed the maximum lipid productivity (0.13 mg/L), and *S. obliquus* removed 155 mg of total nitrogen and 4 mg of total phosphate per gram of dried algae for growth.	[1]
Chlorella vulgaris YSW-04	A 20% concentration of piggery wastewater effluent diluted with distilled water	Light intensity: 45–50 μmol/(m^2·s) Temperature: 27°C Time: 3 weeks	A 20% concentration of wastewater effluent diluted with distilled water was found to be most effective for generating high-efficiency biodiesel and for removing inorganic nutrients.	[32]
Chlorella pyrenoidosa	Ozonated and autoclaved piggery wastewater	Light intensity: 63 μmol/(m^2·s) Temperature: 25°C ± 2°C Time: 12 d	Lipid contents were 22.03% and 22.26% in the piggery wastewater with autoclaving and ozonation, respectively. The removal rate of COD was about 50%–60%.	[30]
Chlorella sp. GD	0%, 25%, 50%, 75%, and 100% piggery wastewater (diluted using the medium)	Light intensity: 300 μmol/(m^2·s) CO_2 aeration rate: 2% Temperature: 26°C ± 1°C Time: 10 d	Highest lipid content and lipid productivity obtained in 25% piggery wastewater were 29.3% and 0.155 g/(L·d), respectively, while the maximum specific growth rate and biomass productivity were 0.839 per dand 0.681 g/(L·d) in 100% piggery wastewater, respectively.	[28]
Chlorella zofingiensis	Autoclaved piggery wastewater and NaClO-pretreated piggery wastewater	Light intensity: 842 ± 778 μmol/(m^2·s) CO_2 aeration rate: 5%–6% Temperature: 29.4°C ± 3.9°C	*C. zofingiensis* was cultivated outdoors with the autoclaved piggery wastewater and could achieve the highest lipid content of 34.82%. *C. zofingiensis* cultivated with autoclaved piggery wastewater could remove 79.84% COD, 82.70% TN, and 98.17% TP, while using the NaClO-pretreated piggery wastewater to culture *C. zofingiensis*, 78.29% COD, 84.49% TN, and 95.26% TP were reduced.	[34]
C. vulgaris JSC-6	Fivefold diluted swine wastewater	Light intensity: 200 W/m^2 For mixotrophic cultivation, 0.2 vvm CO_2 (2.5%) was supplied continuously, while in heterotrophic growth, no CO_2 sparging was provided.	Removal efficiency of COD and NH_3–N were nearly 60%–70% and 40%–90%, respectively, in the mixotrophic and heterotrophic cultures. The highest biomass concentration obtained in fivefold diluted wastewater was 3.96 g/L.	[31]
Chlorella sorokiniana CY1, *C. vulgaris* CY5 and *Chlamydomonas* sp. JSC-04	Diluted (1-20x) anaerobically treated piggery wastewater	Temperature: 20°C–25°C Time: 16–20 d	Highest lipid content and productivity obtained with *C. vulgaris* with Blue Green Medium (BG-11) with 62 mg/L N were 62.5 wt% and 162 mg/(L·d), respectively.	[35]
Scenedesmus sp.	Filtered anaerobically digested piggery wastewater	Light intensity: 100 μmol/(m^2·s) Temperature: 24°C ± 1°C	Highest biomass productivity and the highest lipid productivity were 1.34 g/L and 27.01 mg/(L·d) in 15% and 10% anaerobic digested wastewater groups, respectively.	[36]
C. pyrenoidosa	Diluted primary piggery wastewater with the initial COD of 1,000 mg/L	Light intensity: 63 μmol/(m^2·s) Temperature: 25°C–27°C Time: 10 d	Maximum lipid productivity was 6.3 mg/(L·d) with the initial COD of 1,000 mg/L.	[33]

Table 4
Electricity generation using different microbial fuel cells (MFCs)

Feedstock/substrate	Device	Operation parameters	Results	Reference
Swine wastewater	Two-chambered MFC	Temperature: 30°C pH: 7.0 Aeration rate: 30 mL/min	A maximum power density of 45 mW/m² was achieved, and in single-chambered air cathode MFC tests, the maximum power density achieved was 261 mW/m².	[39]
Piggery wastewater	Loop configuration MFC with relatively large size (5 L)	Aeration rate: 1.5 L/min External resistance: 1,000 Ω	A maximum power density of 1,415.6 mW/m³ at a current density of 3,258.5 mA/m³ was achieved. An organic removal rate of approximately 0.523 kg COD/m³·d with nitrogen removal rate of 0.194 kg N/m³·d was reached.	[40]
Piggery wastewater with COD concentrations of 3,998 ± 13 mg/ L	Anaerobic baffled stacking microbial fuel cells consisting of four individual MFCs with total volume of 6.4 L	Temperature: 18°C–22°C External resistance: 1,000 Ω	Average maximum power generation of four individual MFCs was 178.1 mW/m².	[41]
Swine wastewater	A single-chambered MFC	Temperature: 30°C External resistance: 1,000 Ω	Maximum power density of 228 mW/m² was achieved, while 84% of the organic matter was removed in 260 h.	[38]
Swine wastewater with COD concentrations of 1,652 mg/L	A bio-electrochemical reactor with anodic bio-oxidation coupled to cathodic bio-electro-Fenton	Temperature: 30°C pH: 7.05 Aeration rate: 300 mL/min	Electricity was generated at around 3–8 W/m³ of maximum output power density. The overall removal rates for COD, BOD, NH_3–N, and TOC ranged between 62.2%–95.7%.	[42]

slurry is a kind of high quality organic fertilizer with significant nutrients and abundant organic matter [59]. The gas produced by anaerobic fermentation contains CO_2, due to which, it can be used as a (gas) fertilizer to accelerate the growth of plants. Using biogas slurry as the foliage dressing can also regulate plant metabolism and provide supplementary nutrition to plants. Another advantage of using biogas slurry is that it contains both the organic matter and the humus, which enable it to balance the growth and population distribution of microorganisms. Furthermore, it can generate enhancement in structural, physical, and chemical characteristics of soil, thus resulting in better soil fertility.

According to Islam et al. [60], the application of approximately 70 kg of biogas slurry N per hectare would improve the production of biomass and nutrient content in maize fodder. Yu et al. [61] assessed the effects of concentrated slurry on tomato fruit quality and came up with the conclusion that using concentrated slurry is a practicable means for improving the tomato production. It could enhance tomato's electrical conductivity, increase the amount of organic matter, available N, P, and K, total N and P, and fruit content of amino acids, protein, soluble sugar, β-carotene, tannins, and vitamin C, together with the R/S ratio. It also increased the amount of culturable bacteria, actinomycetes, and fungi in soils.

3.3. Base material utilization

The fermentation product of piggery wastewater can be used as the base material for nutrient soil preparation. Vegetables have a high requirement for nutrients. However, such needs are often difficult to meet using natural soil. Biogas residue can fully meet the requirement due to the variety of nutrients it contains. Moreover, biogas residue helps in balancing the growth and population distribution of microorganisms in soil. For example, higher yield was observed when using biogas residue as the base material during the cultivation of edible fungi [62,63].

3.4. Other resource utilization methods

3.4.1. Microbial flocculant production

Microbial flocculant has the advantages of high efficiency and security over traditional methods. However, its high production cost limits its application on commercial scale. Therefore, microbial flocculant is still at laboratory research stage. Using piggery wastewater as a substitute culture medium to produce microbial flocculant could greatly reduce the cost.

Pei et al. [64] used piggery wastewater as a cheap alternative medium for a bioflocculant-producing bacteria species (B-737). The results showed that the piggery wastewater had a suitable C/N ratio, and that there was no need to add other carbon and nitrogen nutrient sources. With the addition of 1.6 g/L K_2HPO_4 and 0.8 g/L KH_2PO_4 only, the bioflocculant yield of B-737 could reach 1.5 g/L within 10–24 h of fermentation, while the COD and TN of piggery wastewater was reduced by 61.9% and 53.6%, respectively. Qiu et al. [65] investigated the production of bioflocculant by cultivating *Rhodococcus erythropolis* using anaerobic treated

Table 5
Optimal conditions and removal performance of MAP in the reviewed literature

Wastewater characteristics	Optimal parameters	Removal performance	Reference
Mg^{2+}: 345 mg/L PO_4^{3-}: 629 mg/L	N:P ratio: 3:1 Mg:Ca ratio: 2.25:1 Stirring speed: 45–90 rpm Temperature: <20°C	More than 90% of P in the form of large crystals of struvite was recovered under optimal conditions.	[49]
Anaerobically digested swine manure effluent with the Mg:P molar ratio of 0.75:1	pH: 9.0 Mg:P ratio: 1.6:1	Maximum phosphorus removal was 80% under optimal conditions.	[52]
Mg^{2+}: 131 mg/L PO_4^{3-}: 89.5 mg/L	pH: 10.0 Mg^{2+}/NH_4^+ molar ratio: 1.6 PO_4^{3-}/NH_4^+ molar ratio: 1.3	Under optimal conditions, a large amount of struvite was formed within 5 min.	[53]
OP: 189.9 mg/L NH_4^+: 3,033.7 mg/L	Mg:P molar ratio: 0.8–1	19% of total phosphorus (TP) and 15% of total nitrogen (TN) were detected in the recovered sediment, while 65% of TP and 67% of TN in the sediment were recovered in pure struvite.	[54]
PO_4^{3-}: 31.62 mg/L NH_4^+: 2,623.5 mg/L	Electric voltage: 7 V NaCl: 0.06% RT: 1.5 h Initial struvite amount: 1.25 g/L	49.17 mg/L of phosphate (PO_4^{3-}–P) was dissolved, while ammonium–nitrogen (NH_3–N) can be completely removed from the solution.	[55]
NH_4^+: 985 mg/L PO_4^{3-}: 161 mg/L Mg: 6.7 mg/L	pH: 8.0–8.5 Mg:N:P molar ratio: 2.5:1:1	The performance of struvite precipitation progressively decreased with the increase in the number of recycling cycles, while the cost was reduced by 81%.	[50]
Mg: 28 mg/L P_T: 128 mg/L	pH: 9 Mg:P_T molar ratio: 1.2:1	Compared with struvite precipitation using pure chemicals, total ammonia nitrogen (TAN) concentration was decreased to 63 mg/L, and about 37% of the cost could be saved.	[56]
Mg: 21 mg/L P_T: 105 mg/L	pH: 9.5 Mg:N:P ratio: 1.15:1:1	Without the supplementation of additional magnesium and phosphate sources, 80% of TAN could be removed, while with the supplementation of bittern, 91% of TAN and 97% of P_T (total orthophosphate) in swine wastewater could be removed and recovered.	[57]
Mg: 13 mg/L P_T: 103 mg/L	Current density: 2 mA/cm^2	With the supplementation of electrolyzed magnesium alloy, the recovery efficiency of phosphate was 99%.	[58]
Mg^{2+}: 60 mg/L NH_4^+: 706 mg/L PO_4^{3-}: 40.3 mg/L	In SBR, the minimum aeration time was 1.0 h, while in the continuous-flow reactor, the minimum HRT was 6.0 h.	SBR provided 90.5% phosphate removal and 88.4% overall P recovery, while the continuous-flow reactor provided 85.4% phosphate removal and 84.1% overall P recovery.	[51]

piggery wastewater as the substrate. The results showed that the optimum medium for its growth consisted of 10.0 g/L sucrose, 2.0 g/L KH_2PO_4, 5.0 g/L K_2HPO_4, 1.0 g/L NaCl, and 0.2 g/L $MgSO_4$. The optimal fermentation conditions were 30°C, 120 r/min, and medium pH (8.0). After 72 h of fermentation, the flocculating rate of the fermented piggery wastewater could reach 92.57%. Peng et al. [66] produced a new bioflocculant by culturing *R. erythropolisin* in a mixture of sludge and livestock wastewater at the ratio of 7:1 (v/v). Guo and Ma [67] used alkaline-thermal pretreated sludge as a bioflocculant for swine wastewater pretreatment. The COD, ammonium, and turbidity of swine wastewater were reduced by 45.2%, 41.8%, and 74.6%, respectively, when incubated with 20 mg/L at pH of 8.0.

Using piggery wastewater as an alternative medium to produce bioflocculant requires less amount of extra carbon and nitrogen sources, thus reducing the total cost of microbial flocculant. It also provides a new way of resource utilization from swine wastewater.

3.4.2. Seed soaking

Biogas slurry is the product of anaerobic fermentation of piggery wastewater and is rich in nutrients and bioactive substances for seed germination and seedling growth. Additionally, it can provide appropriate ambient temperature for seed germination. Yuan et al. [68] studied the effect of seed soaking with biogas slurry on seed germination and seedling growth of *Tagetes erecta*. The results suggested that an appropriate biogas slurry concentration combined with proper seed soaking time could improve the germination and growth of *T. erecta*. Seeds soaking for 4h in 50% biogas slurry exhibited the highest germination (81.3%) as well as the highest root activity, while the seeds soaking for 5h in 50% biogas slurry developed the longest roots.

3.4.3. Pest control

The anaerobic fermentation slurry is a universal bio-pesticide, containing a variety of nutritional elements, and therefore, has a good controlling effect on crop diseases and insect pests. The NH_3-N in biogas slurry can block nerve conduction and breathing of pests, while low volatile fatty acids in biogas slurry can react with enzymes, receptors, and other substances of insect pests. These two features can cause physiological changes of pests and eventually lead to their death. Zhang et al. [69] analyzed five kinds of anaerobic fermentation slurry compound pesticides, and the results indicated that all of these compound pesticides were able to enhance the killing effect on aphids.

4. Conclusions and future prospects

At present, the resource utilization of piggery wastewater is mainly focused on obtaining and using resources for fertilization and biogas. For the recovery of nutrients, carbon recovery is conducted through biogas projects, of which, the core product is methane. Nitrogen and phosphorus recovery is mainly achieved using struvite crystallization.

Researchers working in the field of biogas have now come up with a biogas-project-linked eco-agricultural engineering model. This model can not only solve the problem of simultaneous disposal of piggery wastewater, agricultural wastes, and other organic wastes, but can also produce high-quality fertilizer and generate energy, which can help resolve the demand–supply deficit in energy sector. After anaerobic digestion of piggery wastewater, the presence of high levels of heavy metals and antibiotics in the residue is a major obstacle in using this resource effectively. The heavy metals in pig farming biogas residues mainly include Zn, Cu, As, Pb, Cd, Cr, Hg, and Ni [70]. Antibiotics' abuse is common in livestock and poultry production industries because of their low bioavailability [71]. In addition, both the heavy metals and the antibiotics have inhibitory effects on anaerobic digestion and anammox activity used for treatment of piggery wastewater [72]. Therefore, there are still safety and feasibility concerns about the use of biogas fertilizer in agriculture, which demands further research and discussion.

As for the recovery of nitrogen and phosphorus, struvite crystallization is one of the most commonly discussed methods. However, the formation of struvite crystallization needs alkaline conditions, due to which, the cost would be relatively high in practical applications. Moreover, struvite is a slow-releasing fertilizer, which is rarely directly used in agricultural production. In addition, the excessive spread of any organic fertilizer on ground or its use under inappropriate soil and weather conditions can lead to pollution of surface water and aquifers [3]. Therefore, the recovery and utilization of nitrogen and phosphorus also faces some challenges. This concern is getting more serious considering that the phosphate is becoming a scarce resource. However, microalgae and MFCs are now considered novel and effective ways for recovering nitrogen and phosphorus from piggery wastewater.

In general, the use of resources from piggery wastewater should be based on four principles, namely the resource recovery, harmlessness, waste reduction, and comprehensive utilization. It is highly desirable, perhaps essential, to develop a circular economy, which organically integrates environmental engineering, ecological engineering, biotechnology, and agricultural engineering. Although there are many technologies available for piggery wastewater treatment, their effective application to pig farms and the design of appropriate ecological treatment modes for different regions in different climates remain very important.

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