



# Research progress and application prospect of anaerobic biological phosphorus removal

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## Abstract

Anaerobic biological phosphorus removal has proposed a new direction for the removal of phosphorus from wastewater, and the discovery of phosphate reduction makes people have a more comprehensive understanding of microbial phosphorus cycling. Here, from the perspective of thermodynamics, the bioreduction reaction of phosphate was analyzed and its mechanism was discussed. The research progress of phosphate reduction and the application prospects of anaerobic biological phosphorus removal from wastewater were introduced, pointing out the situation and guiding the further research in this field.

**Keywords** Phosphate reduction · Thermodynamics analysis · Phosphine · Anaerobic biological phosphorus removal

## Introduction

Phosphorus in water is mainly in the form of inorganic phosphate ions ( $\text{PO}_4^{3-}$ ,  $\text{HPO}_4^{2-}$ , and  $\text{H}_2\text{PO}_4^-$ ). Usually, phosphorus is one of the nutrition in water body for plants and microorganisms in the water. Whereas, when the concentration of phosphorus exceeds the background value of natural water, it will lead to eutrophication in surface water, and the phenomena such as “bloom” and “red tide” will explode. It is a serious threat to water security, a major global environmental issue that has received extensive attention at home and abroad. In order to prevent the eutrophication by the phosphorus content exceeding the threshold, it is necessary to achieve the phosphorus removal from the wastewater. Therefore, there are many researchers devoted to studying phosphorus removal from wastewater. The most commonly used method for removing phosphorus from wastewater is mainly summarized as follows: (a) physical methods based on adsorption and ion exchange (Wu et al. 2014; Liu et al. 2016a; Zhao et al. 2017). (b) Chemical precipitation using magnesium ammonium phosphate or calcium phosphate as the final product (Massey et al. 2010; Qiu et al. 2011; Oladoja et al. 2013). (c) Phosphorus-accumulating bacteria and denitrifying phosphorus accumulating bacteria as functional bacteria are biological

phosphorus removal methods (Yuan and Oleszkiewicz 2010; Wang et al. 2010; Jabari et al. 2014). Generally speaking, biological phosphorus removal would be the most popular method with its low cost and no extra addition. The existing biological phosphorus removal is mainly carried out under alternating anaerobic-aerobic conditions (Zeng et al. 2011; Brdjanovic et al. 2015; Liu et al. 2016b; Zhang et al. 2016; Sun et al. 2017). And the major contributions about biological phosphorus removal in anaerobic-aerobic conditions were made in Europe, the USA, and Japan. But the biological phosphorus removal in anaerobic-aerobic conditions is not the subject reviewed in this paper. Complete anaerobic phosphorus removal is the main body of this study. Since the aerobic system requires a large amount of energy consumption (Gonzalezgil and Holliger 2011; Lochmatter et al. 2013; Nittami et al. 2017), the exploration of a simple, energy-saving, and efficient biological phosphorus removal technology like complete anaerobic dephosphorization is currently a top priority. Thus, anaerobic conditions attract attention.

During the exploration of biological phosphorus removal, it was believed that phosphorus was removed from wastewater into sludge, and it was the breakthrough point that previous researchers focused on. However, in 1988, it was reported that the loss of phosphorus in the phosphorus cycle of a sewage treatment plant was 30 to 40% and that 25 to 50% entered the atmosphere in the form of gaseous phosphine which is toxic and strongly reduces substances as a trace volatile phosphide (Dévai et al. 1988). It was the first time for phosphine to be found in the sludge of biological treatment processes. It might be suggested that under anaerobic conditions, phosphate could

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be reduced by microorganisms. Since then, the role of phosphine in the biogeochemical cycle of phosphorus has attracted researchers' attention. In other words, the discovery of phosphine led to an increased interest in the study of phosphorus removal, not only its transformation into sludge. Rutishauser and Bachofen (1999) compared the production of phosphine in the sludge before and after sterilization. It was found that the sterilized sludge could not produce phosphine, which proved that the production of phosphine was closely related to microorganisms, and it was called phosphate-reducing bacteria. In recent years, researchers have proposed a phosphorus removal scheme based on phosphate reduction reaction, called anaerobic biological phosphorus removal technology (Li 2008; Wei 2010; Liu et al. 2013). It is believed that anaerobic phosphorus removal will not produce a large amount of phosphorus-rich sludge and can absorb gaseous phosphine to achieve phosphorus recovery compared with the traditional method of phosphorus removal. It is small, easy to operate. If successful, anaerobic biological phosphorus removal technology has good prospects for application and popularization. In order to enhance the development of anaerobic biological phosphorus removal technology, it is inevitable to review the research progress of anaerobic biological phosphorus removal based on phosphate reduction.

Although the biological phosphorus removal in anaerobic-aerobic conditions have been studied a lot, at present, the research on anaerobic biological phosphorus removal is limited at home and abroad. The application of anaerobic phosphorus removal to phosphorus removal in wastewater is still in the pilot stage. Herein, this paper will introduce the principle, possible mechanism, and research progress of the development of anaerobic phosphorus removal, providing information for further investigation of anaerobic phosphorus removal.

## Research progress on conversion of phosphate into phosphine

The phosphorus removal could not only be achieved by the transformation into sewage sludge but also by the transformation into phosphine overflowing into atmosphere. It would remove the phosphorus from wastewater and reduce the amount of phosphorus-rich sludge as well, cutting down the cost and difficulties of the sewage sludge further treatment. Technically, the phosphine is produced by the reduction of phosphate since the formation of phosphorus in water is mainly inorganic phosphate ions. Consequently, increasing the production of phosphine is vital for improving the phosphorus removal.

First of all, the release and formation of phosphine from sewage sludge were studied. In 1993, Gassmann and Glindemann first tried to digest soil or sediment with acid or

alkali, and the phosphine released from it was defined as bound phosphine, being named as matrix-bound phosphine (Gassmann and Glindemann 1993). The combined state phosphine was also detected in anaerobic digestion sludge, landfills, surface sediments in harbors, soils, eutrophic lakes, and marine sediments. Experiments have also shown that more than 85% of phosphine exists in the form of matrix-bound phosphine. The release of bound phosphine were compared during the anaerobic growth of the inoculum before and after inoculation, but the maximum was only  $614 \pm 147$   $\mu\text{g}$  (Roels et al. 2002). Then, by monitoring the hydrogen phosphine production of anaerobic granular sludge in absolute anaerobic culture for 10 days, the yield of free phosphine was  $86.42$   $\text{ng} \cdot \text{m}^{-3}$ , matrix-bound phosphine content was  $3.3$   $\text{ng} \cdot \text{kg}^{-1}$  wet mud (Ding et al. 2005). After that, paddy soil was used as the inoculum, after 160 days of continuous anaerobic cultivation, the total phosphorus removal rate of the effluent stabilized at about 25%, and the free phosphine concentration reached  $130$   $\text{ng} \cdot \text{L}^{-1}$  (Wang et al. 2015). A certain research team adopted a sequencing batch reactor to carry out continuous anaerobic culture of sewage treatment plant sludge, and the yield of phosphine was  $7.35$   $\text{ng} \cdot \text{L}^{-1}$  by the way of nitrogen blowing off (Zhang et al. 2010, 2013). On the whole, the production of phosphine in cultures has generally been very low, most of them are nanogram, in research conducted at home and abroad throughout the last few decades. It might limit the progress of this thought of the phosphorus removal. In order to better reduce phosphate to phosphine, it is necessary for a higher and more stable phosphine production system. While along with the research advance, in recent years, some new clues have been found in the actual production process in China. Scholars adopted Sequencing Biofilm Batch Reactor (SBBR) technology to treat sewage in which phosphorus content was about from  $5$  to  $10$   $\text{mg} \cdot \text{L}^{-1}$  without septic tank treatment (Liu et al. 2013). It was found that although the amount of sludge increased after stable operation of the system, the phosphorus content of the sludge decreased. The removal rate of total phosphorus in water could reach more than 70%, and the loss of endogenous phosphorus lost 14.2% of total phosphorus loss, which was presumed to be the production of phosphine. However, it has not verified the existence of free phosphine or matrix-bound phosphine in the system. To sum up the research conclusions of the above scholars, it is easy to find out researchers have different conclusions, even completely contradictory ones. It could also be seen that the production of trace levels of phosphine in the system was low and unstable, and the results of current studies varied widely.

For finding a breakthrough of increasing the phosphine, the sources of phosphorus including inorganic and organic sources, caught the attention of researchers. Scholars have conducted comparative experiments on the best mud source, indicating that chicken manure, pig manure, and anaerobic

sludge all have the potential for phosphate reduction (Guo et al. 2005; Zhou et al. 2007; Wei 2010). Phosphine content and organophosphorus compounds were considered when studying the difference in phosphine content of the sample (Liu et al. 2004, 2006). The content is closely related, and in its subsequent studies, it was confirmed that the phosphine and organophosphorus bacteria showed a very high correlation. Geng et al. (2007) examined the possibility of the two as precursors. It was proved that adding potassium dihydrogen phosphate can significantly increase the concentration of phosphine generated and released, pointing out that inorganic phosphorus was most likely to be a phosphine precursor. However, Zhu et al. (2005) showed that the addition of potassium dihydrogen phosphate had no obvious effect on the release of phosphine, and the addition of lecithin did not play a significant role in the production of gaseous phosphine. Sun (2012) found that compared with phosphine precursors, when potassium dihydrogen phosphate was used as the phosphorus source, the highest removal rate of total phosphorus was 17.9%, and the production of phosphine reached  $82.19 \mu\text{g m}^{-3}$ . In other words, inorganic sources, especially potassium dihydrogen phosphate, remained controversial in increasing the production of phosphine. On the other hand, based on the researches of organic sources, phosphorus-containing materials showed reliable impact on increasing phosphine. The scholars' conclusions are inconsistent. It is speculated that it may be because the different inoculation mud sources used in the system make the difference of initial state of the microbial population structure, which leads to two distinct situations in which the organic phosphorus or inorganic phosphorus can be domesticated successfully and failed.

pH was another significant factor to be studied for increasing phosphine. Ding et al. (2005) studied the effect of pH on phosphine production from anaerobic granular sludge in breweries and found that acid conditions would be more conducive to the release of phosphine. Wan et al. (2013) studied phosphorus removal of piggery wastewater. The cumulative phosphine yield was greatest at pH 5–6, followed by pH = 3–4, pH = 8–9, and pH = 7–8, indicating that under anaerobic conditions, the more acidic environment, the more conducive to phosphine. It is similar to the result of Guo et al. (2005), but the best pH for releasing phosphine is lower. Hence, acidic condition was benefit for the production of phosphine. It can be explained in conjunction with the anaerobic three-stage theory, including the first stage, hydrolysis and fermentation. In this stage, complex organic matter is hydrolyzed and fermented by microorganisms (fermentation bacteria), mainly to convert carbohydrates, proteins, and fats into monosaccharide amino acids, fatty acids, glycerol,  $\text{CO}_2$ ,  $\text{H}_2$ , and so on. In the second stage, hydrogen and acetic acid is produced, called the acidification stage. The third stage is methanogenesis stage, in which the hydrogen-producing acetic acid section and the methane-producing section explain

this phenomenon. Because of competitive use of electrons in methanogenesis and phosphine production, the methanogenic segment inhibits the release of phosphine. The main purpose of the fermentation section is to decompose organic macromolecules into small molecules and produce capacity. But at this time, the energy is lower and the reduction reaction is weaker. Therefore, the production of phosphine in the acidic stage is greater, showing an acidic environment.

Next factor was enzyme. Liu et al. (2006) considered that the production of phosphine has a significant correlation with the activities of alkaline phosphatase and dehydrogenase, and was not related to acid phosphatase. You et al. (2013) demonstrated the surface sediments in Jinpu Bay sea area. There was a significant positive linear correlation between the matrix bound phosphine and alkaline phosphatase. Cao et al. (2017) and Zhao (2017) studied the relationship between alkaline phosphatase and dehydrogenase and phosphine in Anaerobic Sequencing Batch Reactor (ASBR) activated sludge. The former considered that phosphine was positively correlated with alkaline phosphatase and had no correlation with dehydrogenase, and the latter considered that phosphine had a positive correlation with both enzymes and had a stronger correlation with alkaline phosphatase. Alkaline phosphatase (ALP) is a special extracellular enzyme. It has been reported that microorganisms can participate in the mineralization of organic phosphorus in environmental matrix by secreting ALP and play an important role in the natural phosphorus cycle. Dehydrogenase is a special intracellular enzyme, which mainly participates in the process of microbial redox metabolism. It is one of the sources of proton and electron production in microbial electrochemical system. Dehydrogenase can provide certain reducing power in the process of biochemical activity. Dehydrogenase may be a catalyst for phosphine production by microorganisms under anaerobic conditions. The author has elaborated in the article “Relation Between Phosphine Concentration and Alkaline Phosphatase Activity in ASBR System”. Accordingly, alkaline phosphatase could contribute to the release of phosphine.

Based on the research mentioned above, phosphine is closely related to bacteria. Iverson (1968) believes that sulfate-reducing bacteria can reduce phosphates to phosphine. Jenkins et al. (2000) studied and reported some mixed cultures of anaerobic microorganisms including mixed acid fermenting bacteria and butyric acid fermenting bacteria and purebred microorganisms such as *Escherichia coli*, *Salmonella gallinarum*, *Salmonella arizonae*, *Clostridium butyricum*, *Clostridium sporogenes*, and *Clostridium acetobutylicum* in Proteobacteria and Firmicutes can produce phosphine under anaerobic conditions. Luo (2013) used an anaerobic mixed continuous flow reactor to conduct anaerobic phosphorus removal tests, and it was considered that the strain of phosphate reducing bacteria was *Bacillus sphaericus*. It can be seen that the types of bacteria that can produce phosphine

**Table 1** Thermodynamic analysis of methane reactions on various substrates

Reaction formula	$\Delta G^0/$ (kJ·mol <sup>-1</sup> )
$4\text{H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O}$	-139
$4\text{HCOO}^- + 4\text{H}^+ \rightarrow \text{CH}_4 + 3\text{CO}_2 + 2\text{H}_2\text{O}$	-119.5
$4\text{CH}_3\text{OH} \rightarrow 3\text{CH}_4 + \text{CO}_2 + 2\text{H}_2\text{O}$	-103
$\text{CH}_3\text{COO}^- + \text{H}^+ \rightarrow \text{CH}_4 + \text{CO}_2$	32.5

by reducing phosphorus are relatively extensive, but in non-efficient phosphorus biologic reduction, the species of phosphorus reducing bacteria cannot be determined simply with dominant bacteria. Moreover, in the actual wastewater treatment process, the population structure of the organism is always in a dynamic state of change, so from the perspective of sewage treatment, there are still great defects in the study of the population structure of phosphate reduction. It has also been shown that hydrogen phosphide-producing microorganisms usually coexist with other microorganisms in an ecosystem. Mixed microorganisms are more conducive to reducing phosphate to hydrogen phosphide. However, the production of phosphine is mostly considered to be a by-product of microbial life activities, and its role in life activities is still lacking further research. The ecological relationship between the change of microbial population structure and the efficiency of phosphine production is not yet clear. Therefore, exploring the relationship between microbial functional bacteria and phosphine production, and studying the change of microbial population under enhanced phosphine production have a certain reference value for further explaining the mechanism of phosphine production at the microscopic level.

## Thermodynamic analysis of phosphate reduction

There are two possibilities for the phosphate reduction reaction. One is that the organism obtains energy from the phosphate reduction process; the other is that the biomass consumes energy to perform this reduction reaction.

**Table 2** Thermodynamic analysis of sulfate reduction

Electron donors	Reaction formula	$\Delta G^0/(\text{kJ} \cdot \text{mol}^{-1})$
H <sub>2</sub>	$4\text{H}_2 + \text{SO}_4^{2-} + \text{H}^+ \rightarrow \text{HS}^- + 4\text{H}_2\text{O}$	-151.9
Acetic acid	$\text{CH}_3\text{COO}^- + \text{SO}_4^{2-} \rightarrow 2\text{HCO}_3^- + \text{HS}^-$	-47
Propanoic acid	$2\text{CH}_3\text{CH}_2\text{COO}^- + 1.5\text{SO}_4^{2-} \rightarrow 1.5\text{HS}^- + 0.5\text{H}^+ + \text{HS}^- + 2\text{CH}_3\text{COO}^- + 2\text{HCO}_3^-$	-88.8
Ethyl alcohol	$\text{CH}_3\text{CH}_2\text{OH} + \text{SO}_4^{2-} \rightarrow 2\text{CH}_3\text{COO}^- + \text{HS}^- + \text{H}^+ + 4\text{H}_2\text{O}$	-132.8
Lactic acid	$\text{CH}_3\text{CHOHCOO}^- + \text{SO}_4^{2-} \rightarrow 2\text{CH}_3\text{COO}^- + \text{HS}^- + \text{H}^+ + 2\text{HCO}_3^-$	-160.3

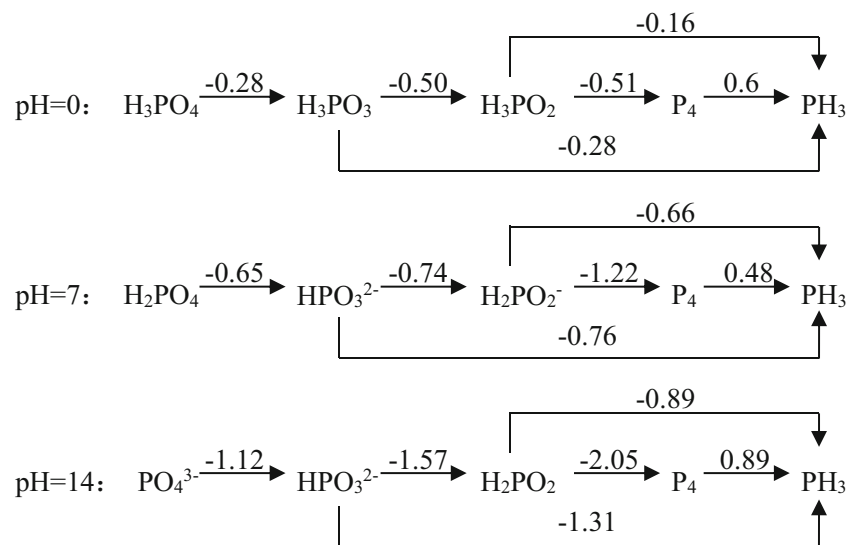
For organisms to obtain energy from the phosphate reduction process, the organism needs a high-energy electron donor. In view of the fact that this electron donor has not yet been found in the current research phase, reference is made to known biochemical pathways for biochemical production of methane and sulfides.

When methane is produced by methane-producing bacteria, H<sub>2</sub> is generally used as an electron donor and CO<sub>2</sub> is an electron acceptor. A large amount of energy is released per mole of CH<sub>4</sub>. The specific reaction pathway is shown in Table 1.

Sulfate-reducing bacteria can use sulfate as an electron acceptor for organic dissimilation. In addition to using H<sub>2</sub>, formic acid, and acetic acid, they can also use fatty acids, sugar, amino acids, and fermented products such as butyric acid, propionic acid, and ethanol. Lactate is the most feasible energy for sulfate reduction as an electron donor, as shown in Table 2. If the organism wants to get energy from the phosphate reduction process, the electron donor may be H<sub>2</sub> or lactic acid, as hydrogen and lactic acid are the current known high-energy electron donors.

The change in electrode potential at each step that may be present in the process of phosphate reduction can be seen from Fig. 1. All phosphorus compounds are not typical oxidants, especially under alkaline conditions, and are even weak for the lowest valence phosphine. The oxidizing agent can also completely oxidize it to orthophosphate. Conversely, if the +5-valent orthophosphate is reduced to phosphine, a strong reducing agent is bound to be required.

Under the standard pH value of 7, using hydrogen or lactic acid as the electron donor, and phosphate reduction reaction is shown in Table 3. From thermodynamic point of view, the Gibbs free energy of phosphate reaction is more than zero, which cannot occur. Under natural conditions, the mass concentration of phosphine is generally within the range of 1 mg m<sup>-3</sup>. When the pH value is neutral, the hydrogen partial pressure is 0.1 kPa, the partial pressure of the phosphine is 10<sup>-7</sup> kPa, the other compounds are 0.01 mol L<sup>-1</sup>, and the Nernst equation is used to calculate less than zero volt. It shows that the reaction of the phosphate to phosphine under natural conditions is the energy absorption reaction. However, as the extreme adverse reaction of nitrogen fixation in nature, the reaction process requires high energy in the process of

**Fig. 1** The electrode potential of phosphate deoxidation

opening, and at neutral condition; it is calculated by the Nernst equation to be  $-1.0$  V. Obviously, the required conditions are more severe than the upper phosphorus reduction. The normal reaction depends on the catalytic action of nitrogenase on the energy released by ATP hydrolysis. It is speculated that certain specific enzymes also play a role in the phosphate-reducing microorganisms.

### Application prospect of anaerobic biological phosphorus removal technology

It is found that phosphate can be reduced to phosphine from anaerobic conditions. Most of the researchers in China have used ASBR as the main research subject, and the focus is mainly on the factors affecting the efficiency of phosphine production.

Ding et al. (2005) studied a large scale Upflow Anaerobic Sludge Blanket (UASB) system for treatment of beer wastewater. The results showed that the concentration of gaseous phosphine in biogas was  $1.94\text{--}17.92$   $\text{ng m}^{-3}$ , which was lower than that of the other phosphine production processes. Since the phosphine concentration of  $\text{mg}\cdot\text{m}^{-3}$  was reported in the early stage of Dévai, Ding recalculated the material balance of phosphorus, and put forward that the loss of phosphorus through biogas was  $4.5\text{--}46.6$   $\mu\text{g}$  per day, accounting for  $(0.434\text{--}4.25) \times 10^{-6}$  ‰. The loss of phosphorus in sludge matrix-bound

phosphine was estimated to be  $42.03\text{--}146.7$   $\mu\text{g}$  per day, accounting for  $(3.82\text{--}14.1) \times 10^{-6}$  ‰. This indicated that in the UASB process, the feasibility of phosphorus removal by means of phosphate reduction to phosphine is very low.

The difference in phosphorus removal efficiency between UASB and Janssen-enhanced biochemical phosphorus removal processes is compared by Li (2008). It is pointed out that although anaerobic microorganisms cannot remove phosphorus by absorbing it, the corresponding volumetric load can be five to ten times higher than that of aerobic sludge. Compared with aerobic phosphorus removal process, the volumetric phosphorus removal rate of UASB was  $3.6\text{--}21.4\text{mP}\cdot(\text{L}\cdot\text{d})^{-1}$ , the removal rate of UCT was  $3.6\text{--}21.4\text{mP}\cdot(\text{L}\cdot\text{d})^{-1}$ , and Phoredex was  $3.6\text{--}21.4\text{mP}\cdot(\text{L}\cdot\text{d})^{-1}$ . It is obvious that UASB is higher than UCT and Phoredex. However, compared with aerobic phosphorus removal process, the phosphorus removal efficiency of UASB was greatly dependent on the sufficient carbon source substrate to provide the energy required for normal metabolism. The C/P ratio had a significant effect on the anaerobic phosphorus removal rate. According to the thermodynamic analysis of phosphate reduction, it takes a lot of energy to reduce phosphate to phosphine, so the higher COD, the more energy produced by organic degradation, and the higher the possibility of reduction.

In recent years, Guangzhou university team mainly (Wei 2010; Zhang 2011; Sun 2012), has studied the effects of the sludge, phosphorus source, pH value, ORP value, and trace

**Table 3** Thermodynamic analysis of phosphate reduction

Reaction formula	$\Delta G^0/(\text{kJ}\cdot\text{mol}^{-1})$	$E_0^\ominus/\text{V}$
$4\text{H}_2 + \text{H}^+ + \text{H}_2\text{PO}_4^- \rightarrow \text{PH}_3 + 4\text{H}_2\text{O}$	+244	-0.32
$2\text{CH}_3\text{CHOHCOO}^- + \text{H}_2\text{PO}_4^- \rightarrow 2\text{CH}_3\text{COO}^- + 2\text{HCO}_3^- + \text{PH}_3 + \text{H}^+$	+237	-0.31
$\text{H}_2\text{PO}_4^- + \text{H}_2 \rightarrow \text{HPO}_3^{2-} + \text{H}_2\text{O} + \text{H}^+$	+46	-0.24



element on phosphine production under anaerobic conditions. The mechanism of anaerobic phosphorus removal was studied. Zhao (2017) sensitively pointed out *Methanobacterium*, *Methanosaeta*, *Methanobacterium*, *Syntrophus*, *Sedimentibacter*, *E6*, *T78*, *DCE29*, and *SHD-231* were the dominant bacteria in the anaerobic phosphorus removal and phosphine production. Once the relevant dominant strains have been isolated and purified and tried to be applied to the actual phosphorus removal process, I believe this will be a qualitative leap. In the future, our work can focus on cultivating an activated sludge system capable of producing phosphine-producing hydrogen, screening for possible phosphine producing strains, and 16srDNA identification, optimizing culture conditions to achieve optimal culture. Finally, through molecular biological identification, the species characteristics and culture characteristics are determined for application.

## Future perspective

Regarding the research on anaerobic biological phosphorus removal, the current problems in the laboratory stage mainly include poor detection accuracy of phosphine, low utilization of biological level detection means, and low phosphate removal rate.

Throughout the previous achievements, there has been no significant progress in the mechanism of anaerobic biological phosphorus removal. At present, the related research still belongs to the macroscopic level, but the output of phosphine is very small, and there are many influencing factors, which is not conducive to the study of the formation mechanism of phosphine. The production process of phosphine should be explored from microcosmic aspects such as microbial phase migration and enzymatic characteristics to explain the biological formation mechanism of phosphine.

Microbes as the main contributor to the process of anaerobic biological phosphorus removal, the dynamic changes of its species and community structure directly affect the efficiency of phosphine production. Therefore, the identification of the phosphine producing strains is done, the method of separating the phosphine producing strains is explored, the living habits and the growth characteristics of the species of the phosphine producing bacteria are studied. It is helpful to optimize the operating state of the system and improve the efficiency of the anaerobic phosphine production. It provides theoretical support for the research and application of the anaerobic phosphorus removal process and the optimization and control of the operation of the anaerobic phosphorus removal process, and is of great significance to the study of the biological phosphine production.

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## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no competing interests.

**Ethical approval** This article does not contain any studies with human participants or animals performed by any of the authors.

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