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Review

A review of phosphorus recovery methods at various steps of wastewater treatment and sewage sludge management. The concept of “no solid waste generation” and analytical methods

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ABSTRACT

Phosphorus deposits around the world are rapidly depleting, therefore phosphorus recovery methods are gaining more and more interest both in science and industry. This article presents the main methods of phosphorus recovery from sewage sludge. The described approaches are divided in two groups: phosphorus recovery from sewage sludge and leachate, and recovery of phosphorus from sewage sludge ashes. The latter seems to have more advantages connected with both ecological and economical aspects. The need for development of “no solid waste generation” strategy is becoming more and more urgent. The concept of comprehensive management of all solid residues after what is currently considered the most ecological process of sewage sludge incineration connected with phosphorus recovery based on acidic extraction, is described in the article. Solid residues after phosphorus recovery from sewage sludge ashes by means of acidic extraction can be stabilized with solid residues after sewage sludge incineration exhaust gas treatment. Such an approach may enable production of phosphoric raw material together with stabilized construction material. Advantages and disadvantages of the discussed approaches are given. An analysis of the composition of ashes produced in different sewage sludge treatment plants indicates that the proposed technology could be successfully applied in most of such units, especially because the concentrations of elements such as K, Mg, Na, P are sufficiently high, respectively 1.5–12.1 g/kg; 9.9–14.9 g/kg; 3.6–13,3 g/kg and 27,4–99,0 g/kg. However, a phosphorus recovery method should be developed separately for each treatment plant. Only then all comprehensive management methods will be ecologically and economically justified. Analytical methods which could be of use at every step of designing a proper phosphorus recovery process are described.

Contents

1. Introduction 00
2. Methods and scope 00
3. Phosphorus in sewage sludge 00
4. Methods of phosphorus recovery from sewage sludge 00
   4.1. Phosphorus recovery from sewage sludge and leachates 00
   4.2. Phosphorus recovery from the sewage sludge ashes from thermal disposal of sewage sludge 00
5. Analytical side of phosphorus recovery 00
6. Discussion on benefits of implementing phosphorus recovery technology in sewage treatment plants 00
7. Summary 00
   Acknowledgements 00
   References 00

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1. Introduction

Phosphorus is increasingly recognized as a strategic raw material. The main reason for this is the growing world population. It is estimated that in the middle of this century our population will exceed 9 billion, which means that food production will have to be increased by almost 30%. Currently, about 82% of the mined phosphorus is used in agriculture, while 7% is used for the production of animal feed. The remaining 11% of the mined phosphorus is used in industry and medicine for the production of pharmaceuticals, oils, detergents, or even textiles (Cordell et al., 2009; Sorensen et al., 2015; de-Bashan and Bashan, 2004). The demand for food increases with population growth, which is evident in the third world countries, whereas in the developed countries the importance of industry is quickly increasing, which causes phosphorus consumption to increase faster and faster. For this reason, according to the International Water Management Institute, by 2050 the production of phosphorus will grow by 70% overall and even by up to 100% in developing countries, in order to satisfy the rapidly growing demand for phosphorus (Guedes et al., 2014; Zhou et al., 2016). An equally important factor in determining the strategic nature of this element is the fact that natural deposits of phosphorus are not evenly distributed throughout the Earth. The main global phosphate rock deposits are in Morocco, the US, China, South Africa and Jordan, 74% of which are found in Morocco alone (Nakakubo et al., 2012; Cordell et al., 2009; Sorensen et al., 2015; Kataki et al., 2016). The largest amounts of phosphorus are mined in China, the United States has the largest reserves, while South Africa exports the largest quantity. Therefore, the geopolitical situation can have a significant impact on the availability and price of phosphorus, not only in Europe, but in every corner of the world (Guedes et al., 2014).

All over the world there are heated debates about when the global phosphorus resources will be exhausted. According to optimistic estimations of apatite ores, which are the main natural phosphorous deposits, it will not happen for at least 200 years (Tan and Lagerkvist, 2011). Many scientists claim, however, that the deposits will be exhausted as early as in 100–130 years (Li et al., 2014). It should be mentioned that these are reports from about a decade ago, and forecasts made after 2008 are increasingly less optimistic. Currently, there are even mentions that the natural deposits of phosphorus will suffice for only 50–60 years (Tao and Xia, 2007). Some literature data report that by 2050 only 18% of phosphorus deposits will be exhausted, others claim that by the year 2200 the quality of phosphorus ores will be unsatisfactory, making the 11 000 million tons of remaining global phosphorus ores impossible to exploit. The issue of when the deposits of this raw material will really deplete can still be a subject of discussion (Sorensen et al., 2015; Shu et al., 2006; Kataki et al., 2016). However, the fact is that the quality of the available deposits of phosphorus is getting lower. It is already known that only 20% of the phosphorus which is cheap to extract may be suitable for use in agriculture. The rest of the deposits contain too high levels of heavy metals, especially cadmium, and radioactive elements, such as uranium or radon (Pettersson et al., 2008; Cordell et al., 2009; Weigand et al., 2013).

Factors such as the quality of the natural deposits of phosphorus, their availability, and even the geopolitical situation, cause the prices of phosphorus fit for use in agriculture to grow fast. From 1950 to 2000 they increased tenfold; in 2007 alone they grew by about 200%, and in the years 2007–2008, in less than 14 months they rose by 700–800% (Tan and Lagerkvist, 2011; Guedes et al., 2014). That is why scientists are increasingly interested in the methods of phosphorus recovery. Unfortunately, there is still a lack of legal regulations concerning recovery of phosphorus from waste materials (Biplob et al., 2009; Sorensen et al., 2015; Pettersson et al., 2008; Cordell et al., 2011).

Today there are more than 30 kinds of technologies of phosphorus recovery from sewage sludge and new ones are constantly being created (Cordell et al., 2011). All of them carry both risks and opportunities. The biggest disadvantage of the previously presented works on phosphorus recovery methods is a lack of complex management of waste materials and residues which are inevitably produced during the processes. Moreover, some of them are economically unjustified or designed in a way that cannot be implemented on the technical scale. The concept proposed in this paper assumes holistic management of all streams of solid waste generated during the phosphorus recovery process and sewage sludge thermal utilization. Only with the introduction of individual solutions it is possible to design an ecological and economical method of phosphorus recovery connected with the management of the remaining sludge and other process waste generated during sewage treatment.

2. Methods and scope

This study focuses on describing methods of phosphorus recovery from sewage sludge and presenting the concept of "no waste generation". Advantages and disadvantages of the described approaches are presented together with thorough evaluation of selected technologies. Analytical methods are described as powerful tools supporting both phosphorus recovery and the whole sewage sludge management process. The review is based on literature from all over the world but focusing mainly on reports from Europe and Asia since scientists from those regions show high interest in the presented subject. Studies published in technical journals and books are also mentioned. Flow sheets and as-built documentations were used to describe the proposed concept of "no solid waste generation" technology. Additional data on the elemental composition of sewage sludge and ashes were obtained from two polish facilities which are interested in the proposed technology: Sewage Sludge Treatment Plants "Wschód" in Gdańsk and Group Sewage Sludge Treatment Plants in Łódź.

3. Phosphorus in sewage sludge

Many organic waste materials contain significant amounts of phosphorus in various forms: organic, poorly absorbed by plants, and inorganic, better assimilated by plant organisms. Sewage sludge contains the second greatest amounts of this element. The only organic waste containing more phosphorus is bone meal, but on a global scale it is produced in much smaller quantities than sludge. Therefore, sludge is considered a very promising source of phosphorus (Cordell et al., 2011; Havukainen et al., 2016).

Phosphorus must be separated from the wastewater stream flowing out of the treatment plant, because too much phosphorus brought to the natural reservoirs could exacerbate eutrophication, which by stimulating the growth of algae and other photosynthetic organisms may ultimately lead to the formation of extinction zones in the sea, called the deserts of the sea. Such a phenomenon was first observed in a first half of 20th century (Ashley et al., 2011). Currently, the most widely used technology of biological treatment is conducting alternating aerobic and anaerobic processes, called enhanced biological phosphorus removal (EBPR). The first step is to carry out the anaerobic process, during which the organisms in the activated sludge hydrolyze polyphosphates and release phosphorus from cells in the form of orthophosphates, absorbing simple organic compounds from the environment and storing them in the

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