Resources, Conservation and Recycling 105 (2015) 325–346

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Overview and description of technologies for recovering phosphorus from municipal wastewater

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ARTICLE INFO

Article history:
Received 27 April 2015
Received in revised form
23 September 2015
Accepted 24 September 2015
Available online 14 November 2015

Keywords:
Phosphorus
Recovery efficiency
Heavy metals
Digester supernatant
Sewage sludge
Sewage sludge ash

ABSTRACT

Over the past years, numerous technologies have been developed to recover phosphorus (P) from waste streams to repair currently broken nutrient cycles. These developments were largely triggered by environmental considerations (sustainability, resource efficiency), concerns regarding the finite and geopolitically concentrated deposits of raw phosphate ore, and phosphate price increases. Municipal wastewater is a promising and viable source to recover P in larger quantities, to re-establish a circular economy and therefore increase net use efficiency. This work compiles the latest knowledge on approaches to recover P from municipal wastewater and related waste flows with a specific focus on the existing well-developed wastewater management infrastructure, available in significant parts of Europe (e.g., secondary treated effluent, digester supernatant, sewage sludge, sewage sludge ash). About 50 technologies were identified at various levels of development (industrial-, full-, pilot- and laboratory scale). The current selection of P recovery processes is broad and ranges from simple precipitation of dissolved P to complex multi-step approaches, and only a few of these displayed potential for full-scale implementation. They are discussed with regard to their technical principles, process parameters, recovery efficiency, resource demand, possible effects on wastewater treatment, waste flows, and fate of pollutants. We also evaluated them with respect to their rates of P removal from wastewater and their access points of P recovery. For selected technologies, material flow models are presented to facilitate the understanding of even complex processes. This work serves as a basis for future integrated comparative assessments of selected recovery approaches according to technical, environmental and economic criteria.

1. Introduction

Given the important role of phosphorus (P) containing mineral fertilizers in the total global supply of P (~80%; Prud'Homme, 2010), future demand will clearly be driven by developments in the agricultural sector. Agriculture's demand for P will primarily be affected by population growth and changes in diet in part due to rising living standards in emerging and developing countries (Metson et al., 2012; Heffer and Prud'Homme, 2011). Countries lacking P deposits are entirely dependent on imports and are vulnerable to market fluctuations in fertilizer prices to ensure agricultural production and food security. The availability of the resource P is dynamic and dependent on price and technology (Scholz and Wellmer, 2013). National P balances demonstrate that European countries with enhanced wastewater collection and treatment (biological carbon removal and P removal, see Section 2.2) possess a large but often exploited and inefficiently used potential source of P in waste streams, especially in municipal wastewater of ~1 kg P cap^{-1} yr^{-1} (Cordell et al., 2011; Egle et al., 2014a; Gethke-Albinus, 2012; Binder et al., 2009). However, globally human extractions are a very small part of the global anthropogenic P flows. Considering P losses and efficiency, proper manure management is certainly at least as important as sewage management (Scholz et al., 2014). In some countries, the imported P with feedstuff even submerges P in sewage. Direct agricultural application of wastewater (still practiced in many parts of the world) and sewage sludge is the simplest method of P recycling, although the plant availability of sewage sludge P is debated (Kahiluoto et al., 2015; Krogstad et al., 2005). Due to potential environmental and health risks primarily from heavy metals (HM), persistent organic pollutants (POPs), and pathogens, acceptance of direct sludge applications is low or decreasing in many European countries (Ott and Rechberger, 2012). Consequently, alternative disposal methods focus on co-incineration (cement kilns, power plants or municipal solid waste incinerators) where P is the irretrievably lost.

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http://dx.doi.org/10.1016/j.resconrec.2015.09.016
0921-3449/

Table 1
Characteristics of the potential flows for P recovery (Europe countries, Montag, 2008; modified).

Source	Mass flow	P concentration/PO_4-P concentration	P specifics	P recovery potential (%)
Untreated wastewater	200 L cap^{-1} d^{-1}	~10 mg P L^{-1}	Bound/dissolved	100
(1) Urine	~1.5–2 L cap^{-1} d^{-1}	~150–250 mg PO_4-P L^{-1}	Dissolved	30–50
(2) Secondary treated effluent	200 L cap^{-1} d^{-1}	~5–10 mg PO_4-P L^{-1}	Dissolved	50–70
(3.1) Digested sewage sludge (SS) (~3.5% TS[a])	1.6 kg cap^{-1} d^{-1}	Dissolved part: 20–400 PO4-P mg L^{-1}	Partly dissolved (10–30%)	10–30
(3.2) Digester supernatant	1–10 L cap^{-1} d^{-1}	20–400 PO_4-P mg L^{-1}	Dissolved	10–30
(4.1) Digested sewage sludge (~3.5% TS[a])	1.6 kg cap^{-1} d^{-1}	1.4 g P kg^{-1} sludge	Bound (bio/chem); partly dissolved	90
(4.2) SS thickened (10% TS[a])	0.6 kg cap^{-1} d^{-1}	4 g P kg^{-1} sludge	Bound (bio/chem)	90
(4.3) SS dewatered (30% TS[a])	0.2 kg cap^{-1} d^{-1}	12 g P kg^{-1} sludge	Bound (bio/chem)	90
(5) Sewage sludge ash	0.03 kg cap^{-1} d^{-1}	50–130 g P kg^{-1} TS	Bound (chem)	~90

[a] TS (total solids).

Potential methods of P recovery from wastewater consist of direct the separate collection of urine, secondary treated effluent from wastewater treatment plants (WWTP), digester supernatant, sewage sludge (SS) and sewage sludge ash (SSA) (Montag, 2008). These flows differ widely in terms of volume, P concentration, the form of P (dissolved as orthophosphate or biologically/chemically bound), the characteristic of the source (liquid, liquid/solid, solid), pollutant content (HM, POPs, pathogens) and the theoretical recovery potential (Table 1). An ideal approach would feature a high P recovery rate, economic efficiency, and a useful product with low environmental risks. Currently, well-developed and large-scale approaches differ appreciably in terms of these criteria. This article focuses exclusively on approaches for recovering P from municipal wastewater streams. The P recovery approaches address WWTP with strict European standards in P removal for land-locked countries (EC, 1998) and thermal sludge treatment options, namely fluidized bed reactors, which are state of the art in Europe. The general procedures of P recovery approaches have been published frequently, but the important details are frequently lacking (Montag et al., 2011).

Some approaches have received more attention than others have in the past and as such, we have varying degrees of knowledge about them. P recovery by precipitation from sources of dissolved P (orthophosphate) has been investigated in detail (Muster et al., 2013; Rahman et al., 2014; Doyle and Parsons, 2002). Therefore, optimum process parameters, resource demands, effects on WWTPs and characteristics of the products are well known. To recover P from sewage sludge, various sludge treatment options such as anaerobic treatment, thermal hydrolysis, (wet-) oxidation or wet-chemical leaching are necessary as a first step to dissolve P. The behavior of P and process inhibiting ions (Fe, Al, heavy metals) has been well studied and extensively described (Section 3.4). This knowledge is fundamental for taking further steps in pollutants removal and final P recovery. The same applies to procedural challenges, practicability, waste flows, and possible effects on the functioning of WWTPs. For metallurgic approaches, there is a lack of reliable data regarding mass balances and the fate of heavy metals within the process, and only the results of a few trials are available (Ingitech, 2009). Surprisingly, the current literature on P recovery from ash primarily describes approaches with little realistic potential for prospective practical application (Petzet et al., 2012; Donatello et al., 2010; Franz, 2008; Levlin, 2001). In contrast, SSA is already used to create recycled products using industrial processes (e.g., ICL Fertilizers®: fertilizer industry; Thermphos®: production of P_4; EcoPhos®: production of phosphoric acid or animal feed). Numerous approaches have been developed in universities and private companies currently operating at pilot scale or full-scale, but details are not yet widely published. In general, many approaches for recovering P from ash are similar to those for treating raw phosphate ore (Nielsson, 1989). This article provides an overview on known approaches looking in detail at those with potential for full-scale implementation or which are already implemented. These approaches are characterized in the context of P removal from wastewater and at other access points of recovery (Fig. 1). Thus, a first criterion is the characterization of the optional P flows, thereby outlining the challenges for recovery technologies. Based

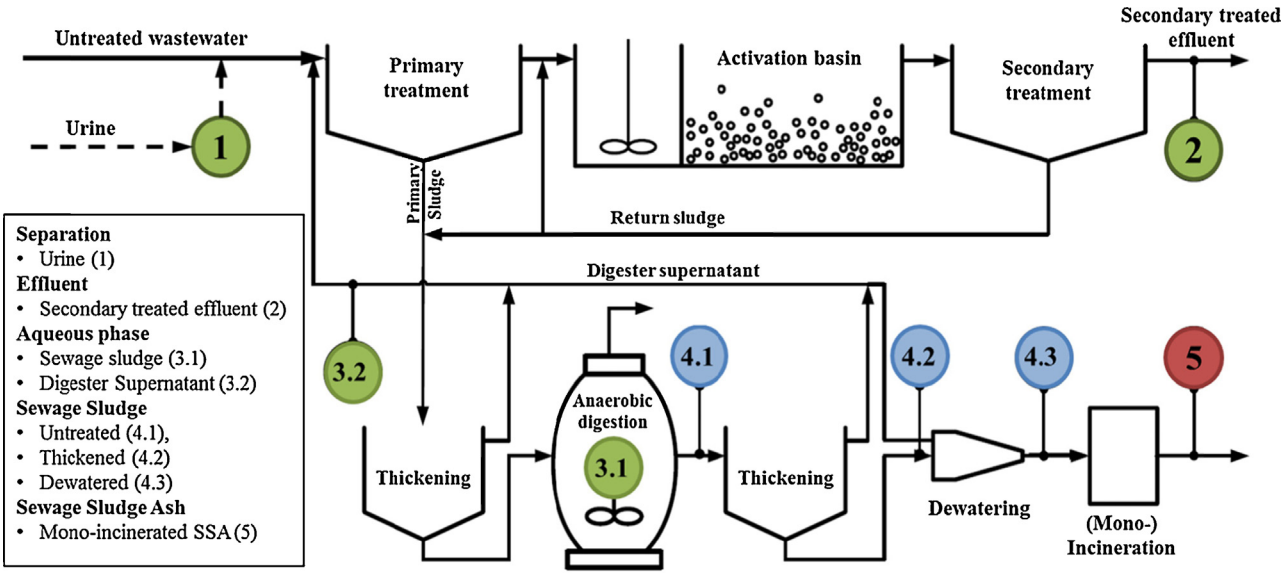

Fig. 1. Various possible access points for P recovery approaches during wastewater and sewage sludge treatment or before/after incineration (Montag, 2008; sketch modified).