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Review

Trends in the recovery of phosphorus in bioavailable forms from wastewater

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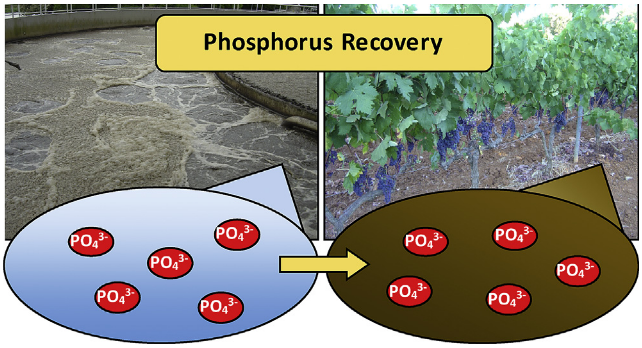
HIGHLIGHTS

- P recovery is a pressing issue and wastewater provides a substantial opportunity.
- Struvite/Ca-P crystallisation can be limited to <25% recovery of influent P load.
- Crystallisation, thermo- and wet-chemical processes are being commercially applied.
- Revised fertiliser legislation and P limits drives wider adoption of technologies.
- All approaches should focus on obtaining agriculturally effective forms of P.

GRAPHICAL ABSTRACT



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ABSTRACT

Addressing food security issues arising from phosphorus (P) scarcity is described as one of the greatest global challenges of the 21st Century. Dependence on inorganic phosphate fertilisers derived from limited geological sources of P creates an urgent need to recover P from wastes and treated waters, in safe forms that are also effective agriculturally – the established process of P removal by chemical precipitation using Fe or Al salts, is effective for P removal but leads to residues with limited bioavailability and contamination concerns. One of the greatest opportunities for P recovery is at wastewater treatment plants (WWTPs) where the crystallisation of struvite and Ca-P from enhanced biological P removal (EBPR) sludge is well developed and already shown to be economically and operationally feasible in some WWTPs. However, recovery through this approach can be limited to <25% efficiency unless chemical extraction is applied. Thermochemical treatment of sludge ash produces detoxified residues that are currently utilised by the fertiliser industry; wet chemical extraction can be economically feasible in recovering P and other by-products. The bioavailability of recovered P depends on soil pH as well as the P-rich material in question. Struvite is a superior recovered P product in terms of plant availability, while use of Ca-P and thermochemically treated sewage sludge ash is limited to acidic soils. These technologies, in addition to others less developed, will be commercially pushed forward by revised fertiliser legislation and foreseeable legislative limits for WWTPs to achieve discharges of <1 mg P/L.

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1. Introduction

Phosphorus (P) is an essential plant nutrient and makes up around 0.2% of plant dry weight (Jiang and Yuan, 2015; Schachtman et al., 1998). In aquatic ecosystems, low concentrations of P benefit the biological productivity of freshwater lakes, reservoirs and rivers. Concentrations of just ~0.02 mg P/L can be considered to cause eutrophication (Correll, 1998), having negative ecological effects where promoted algal growth (Yao et al., 2013) can cause hypoxia and negative effects from algal toxins (Bláha et al., 2009; Žegura et al., 2011).

Detrimental impacts within ecosystems caused by an excess of P has led governments to limit the P concentration in waters. As a whole, the Water Framework Directive 2000/60/EC (European Commission, 2008) in conjunction with the Council Directive 91/271/EEC concerning urban wastewater treatment (European Commission, 1991), identify sensitive areas where high levels of P would have large ecological impacts – and enforce the control of P in wastewater discharges, respectively. As an annual average, it is required that P concentrations within wastewater effluents are below 1–2 mg P/L, depending upon the sensitivity of the receiving environment and the size of the wastewater treatment plant (WWTP), or are reduced by 80% from the influent concentration (European Commission, 1998, 1991). Austria, Germany and Switzerland have now made P recovery mandatory from municipal sewage sludge (European Sustainable Phosphorus Platform, 2017).

The P loading within many ecosystems is a result of P discharges from WWTPs or the use of P in agriculture. Fig. 1 summarises key P flows and losses throughout the global agricultural production and food consumption system. The inorganic P cycle is extremely inefficient and wasteful. Losses of P to natural water bodies from wastewater discharge represents approximately 10% of inorganic P derived fertiliser applied to arable soil globally (see “A” in Fig. 1). These losses create both a need and an opportunity, with respect to P recovery and re-use, needed not only to ensure good ecological status of waterways, but also to maintain the global productivity of agriculture.

With increasing global populations and increased difficulty in accessing P reserves, many studies have raised concerns regarding depletion of mined P sources (Childers et al., 2011; Cordell et al., 2011, 2009; Cordell and Neset, 2014; Gilbert, 2009; Smil, 2000; Withers et al., 2014). Mined P rock exists mostly in ancient marine sedimentary deposits, the majority of which are situated in Morocco and Western Sahara (Van Kauwenbergh et al., 2013). Estimated at ca 67 000 Mt (USGS, 2014), the global production of P rock is widely thought to hit a peak this century (Walan et al., 2014), with some predicting that economically mineable P rock reserves could become scarce or exhausted within 100 years (Childers et al., 2011; Cooper et al., 2011; Smil, 2000). The decreasing quality of P rock, in terms of contamination with cadmium for example (Mar and Okazaki, 2012), and price spike events (Mew, 2016) are additional concerns. With an expanding global population relying on decreasing and deteriorating P resources, the development of technologies for improved recovery and re-use of P is becoming an increasingly urgent environmental, economic and societal issue. The rising cost of P rock extraction will inevitably favour the development of these technologies.

WWTPs provide one of the biggest opportunities for P recovery (Schoumans et al., 2015; Smil, 2000) given the relatively high and constant P load in sewage. The recovery of P from wastewaters can provide an array of benefits: (1) meeting the effluent P limits required by legislation; (2) reducing eutrophication problems; and (3) providing a potential source of fertiliser of agricultural and economic value. The latter simultaneously reduces the reliance on inorganic (rock-P derived) fertilisers in agriculture.

However, municipal wastewaters contain many contaminants, both organic and inorganic, including heavy metals and metalloids (Nguyen et al., 2013), pesticides (Köck-Schulmeyer et al., 2013), pharmaceuticals (Antoniou et al., 2013), personal care products (Brausch and Rand, 2011), nanomaterials, perfluorinated compounds (PFCs) (Richardson and Ternesa, 2014), hormones (Loos et al., 2013), recreational drugs (Wilkinson et al., 2016) and pathogens (Cai and Zhang, 2013). Therefore, the application of untreated effluent to agricultural land would pose associated risks to human food consumption (Schoumans et al., 2015). Hence, wastewaters generally require recovery processes with a certain degree of selectivity to remove P into a solid form that can be safely and effectively used as fertiliser.

Here we critically review P recovery technologies currently used in WWTP processes (chemical precipitation, enhanced biological P