Review

Phosphorus recovery as struvite from farm, municipal and industrial waste: Feedstock suitability, methods and pre-treatments

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ABSTRACT

Global population growth requires intensification of agriculture, for which a sustainable supply of phosphorus (P) is essential. Since natural P reserves are diminishing, recovering P from wastes and residues is an increasingly attractive prospect, particularly as technical and economic potential in the area is growing. In addition to providing phosphorus for agricultural use, precipitation of P from waste residues and effluents lessens their nutrient loading prior to disposal. This paper critically reviews published methods for P recovery from waste streams (municipal, farm and industrial) with emphasis on struvite ($MgNH_4PO_4 \cdot 6H_2O$) crystallisation, including pre-treatments to maximise recovery. Based on compositional parameters of a range of wastes, a Feedstock Suitability Index (FSI) was developed as a guide to inform researchers and operators of the relative potential for struvite production from each waste.

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1. Introduction

1.1. Phosphorus: concerns and possibilities

The global population is projected to rise by 40% from 7.2 billion individuals in the year 2013 to 9.6 billion by the year 2050 (UN, 2014) with food consumption increasing at a rate of 3.1% per year (Heffer and Prud'homme, 2014). Requirements for food security necessitate the sustainable intensification of agricultural production towards supporting productivity gains and income generation (Zapata and Roy, 2004); to meet this demand agricultural productivity is expected to grow by 60% (FAO, 2013). Fertile soils are the key to sustainable production of crops for food, feed and fibre and essential for supporting rural livelihood needs, however few soils are fertile without the addition of plant-available nutrients from organic matter (manure) and commercial fertiliser (Dawson and Hilton, 2011). Commercial fertilisers depend upon the continuing availability of rock phosphate reserves (Heckenmüller et al., 2014); however it has been predicted that the global supply of phosphorus (P) will run out in under 70 years. P is readily fixed by other chemical constituents (e.g. Ca, Fe, Al, Mg, K) making it a key limiting factor in soils globally (Shen et al., 2011), with consequences including reduced yields, delayed maturity and lowered disease resistance across 40% of the world's arable soils (Vance, 2001). Agro-ecosystems account for 80–90% of the world's total P consumption (Childers et al., 2011) with 41.8 Mt of P fertiliser consumed in 2013 globally (Heffer and Prud'homme, 2014). Global P demand is forecast to grow at an annual rate of 1.9% over the period 2013 to 2018 (Heffer and Prud'homme, 2014) with consumption stabilised in the developed countries, but demand increasing in the developing world (Heffer and Prud'homme, 2010). In this context, recovery of P through efficient and economically viable processes from non-conventional P-rich sources such as wastes and residues is clearly a priority for sustainable development.

Understanding of the sedimentary biogeochemical cycle of P is helpful to identify the possible P sinks in nature for effective P management. During the cycling of P in the terrestrial and aquatic environment, significant amounts of P end up in P-rich waste from farms, municipal wastes and industrial processes, prompting recent calls for changes in waste management strategies to promote recycling of waste P. The most common method of P recovery is through production of mineral or salt precipitates from P-rich sources such as the mineral struvite (magnesium ammonium phosphate; $MAP/MgNH_4PO_4 \cdot 6H_2O$) (de-Bashan and Bashan, 2004). Struvite by mass is 44% crystal water, 39% phosphate, 10% magnesium, and 7% ammonium (Gell et al., 2011) and its precipitation requires the presence of three ionic species, magnesium (Mg^{2+}), ammonium (NH_4^+) and orthophosphate (PO_4^{3-}) in an alkaline solution with an optimum molar ratio of 1:1:1 (Rahaman et al., 2008). The factors that govern the precipitation of struvite in P-rich sources include: pH, the ionic strength of solution (Nelson et al., 2003), the presence of impurities or non-participating ions (Le Corre et al., 2007), the mixing energy (Wang et al., 2006), the residence time of suspension during crystallisation (Kozik et al., 2013) and the nature of the reactor used for crystallisation (Koralewska et al., 2009).

Struvite is an ideal alternative fertiliser since it is a non-odorous, non-sludgy crystal which releases nutrients slowly (Bouropoulos and Koutsoukos, 2000) and has low solubility in water thus avoiding eutrophication problems that may arise from other P fertilisers (Zhang et al., 2012). Woods et al. (1999) demonstrated that P recovery from sewage sludge via formation of calcium phosphate granules resulted in reduced biosolid concentrations of 11–49% when a Crystalactor® fluidised bed reactor was used as a tertiary application following conventional biological treatment, compared to conventional treatment without the P recovery step. When sidestream Crystalactor technology was applied with enhanced biological nutrient removal (EBNR), reductions in biosolids ranged from 5% to 30% compared to EBNR only. Technologies that reduce the disposal volume of sludge are environmentally useful since the waste becomes suitable for environmental disposal (Gell et al., 2011). Integration of a nutrient recovery plan with a waste management system will result in cost efficient relocation of excess nutrients (Burns and Moody, 2002).

Whilst struvite recovery has been widely investigated as a waste water treatment method (Munch et al., 2001), it is only recently that its prospects as an alternative P-rich fertiliser source have been realised. Here we review the different approaches taken for struvite recovery, i.e. suitability of sources from farm, municipal and industrial origin, scales and method of pre-treatments and production to enhance struvite recovery.

1.2. Spontaneous struvite precipitation and issues concerning prevention

Spontaneous struvite precipitation in pipes and containers in wastewater treatment processes is often seen as a nuisance which can reduce system efficiency and increase operational cost (Jaffer et al., 2002). Struvite scale formation is found frequently in anaerobic digester units, digester liquor discharge line, heat exchangers and in centrifuge dewatering units downstream of the digester system of wastewater plants. Struvite occurs in regions of high turbulent flow (e.g. in valves, pipe joints and aeration assemblies) when concentrations of Mg^{2+}, NH_4^+ and PO_4^{3-} are favourable and the mixing energy is appropriate (Bhuiyan et al., 2007). In such zones, degassing of carbon dioxide results in localised increase in pH favouring struvite formation (Wu et al., 2005). During anaerobic digestion of waste water sludges, mineralisation of nutrients bound to organic matter occurs (Seadi and Lukehurst, 2012) forming phosphate (also known as orthophosphate). NH_4^+ is becomes available from the degradation of nitrogenous material in organic wastes and this increases the potential of struvite formation (Bhuiyan et al., 2007). Sometimes recirculation of digested effluent from an advanced treatment unit to a previous treatment unit is carried out to obtain a lower concentration of total solids and biochemical oxygen demand, which subsequently causes nutrient looping (Evans, 2007; Fattah and Chowdhury, 2014). Returning of sludge dewatering liquors to previous treatment units has been