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Biosolid Application to Agricultural Land—a Contribution to Global Phosphorus Recycle: A Review

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ABSTRACT

Phosphorus (P) is an essential nutrient required for plant development. Continuous population growth and rising global demand for food are expected to increase the demand for phosphate fertilizers. However, high-quality phosphate rock reserves are progressively becoming scarce. Part of the increased pressure on P resources could be alleviated by recycling P present in biosolids. Therefore, it is crucial to understand the dynamics of P in biosolid-amended soils, the effects of residual biosolid-borne P in soils, the way in which microorganisms may control P dynamics in biosolid-amended soils and the environmental implications of the use of biosolids as a source of P. Further research is needed to maximize biosolid-borne P uptake by crops and minimize its loss from biosolid-amended soils. The analysis of the microbiological control of P dynamics in biosolid-amended soils indicates interactions of biosolid P with other nutrients such as carbon (C) and nitrogen (N), suggesting that harmonization of the current regulation on the use of biosolids in agriculture, mainly based on total N and pollutant contents, is needed to better recycle P in agriculture.

Key Words: anthropogenic P, phosphate, P availability, P biogeocycle, P uptake, runoff P

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INTRODUCTION

Phosphorus (P) is an essential nutrient for all forms of life. Biomolecules containing P are present in cellular components, including membranes (phospholipids), genetic material (DNA and RNA), and energy storage (ATP and ADP), among others (Elser, 2012). While humans and animals satisfy their need for P *via* food intake, plants have to absorb it from soils. In spite of its wide distribution in nature, P is one of the least available mineral nutrients to plants (Goldstein *et al.*, 1988), and P uptake is usually a growth-limiting factor (Grant *et al.*, 2005). Unlike nitrogen (N), the biogeochemical cycle of P does not include a significant gaseous component, since its annual atmospheric deposition rates are in the order of 0.25 kg P ha^{-1} year^{-1} (Liu Y *et al.*, 2008). In natural ecosystems, P is entirely supplied from the weathering of parent materials (Schlesinger and Bernhardt, 1997), and the amount of total P is preserved because it is released back to the soil system through plant residues, animal excreta or when organisms die. In agricultural systems, crop removal represents the primary route by which P is lost from soils. Unless P sources are artificially incorporated to agricultural soils, both total and available P stocks steadily decrease with time to the point that the soil can no longer adequately supply plant P needs (Van Vuuren *et al.*, 2010). In the course of time, soil P depletion may lead to loss of soil fertility and productivity.

Mineral phosphate fertilizers are the primary source of P input to agricultural lands. Even though the use of rock phosphate-based fertilizers was introduced in the 1820s, it was not until the late 1940s that P fertilizers were increasingly requested. In 2011, global phosphate fertilizer production resulted in the depletion of approximately 20 Mt of P from phosphate rock (Jasinski, 2013). The demand for P is expected to increase in the following years due to continuous population growth and rising global demand for food, with a predicted increase to approximately 257 Mt by 2017 (Heffer, 2013; Jasinski, 2013). Economic, high-quality

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phosphate rock reserves are progressively becoming scarce (Cordell and Neset, 2014). Although reserves of phosphate rock are found in several countries and new reserves have been identified (Midgley, 2012), phosphate rock is a finite, non-renewable resource. According to the U.S. Geological Survey, phosphate deposits will last about 50 years at the current rate of extraction (Kelly and Matos, 2013). Therefore, there is an increasing concern regarding phosphate rock reserves to become depleted.

Part of the increased pressure on P resources could be alleviated by recycling P present in various agricultural and urban wastes (Frossard *et al.*, 2009; MacDonald *et al.*, 2011). However, the joint effects of poor knowledge of P status and the lack of a clear regulation on manure or organic waste agricultural management still limits P recycling potential in agriculture. This paper reviews the availability and environmental fate of P present in biosolids and envisages some possible strategies for its sustainable management.

BIOSOLIDS AS A SOURCE OF P

Land application of organic by-products is an economically attractive waste management strategy, largely promoted by scientists and regulating organisms. Furthermore, it has been a socially accepted practice for decades in many parts of the world (Tsadilas, 2011; Larney and Angers, 2012; Lu *et al.*, 2012).

The term biosolid was introduced in the early 1990s to designate the solid, semi-solid or liquid materials generated from the treatment of domestic sewage sludge that has been sufficiently processed to be safely land-applied. Biosolids contain organic carbon (C), N, P, potassium (K), sulphur (S), calcium (Ca), magnesium (Mg), and microelements necessary for plants and soil fauna to live. Nutrient contents in biosolids depend on the untreated water source, chemicals used for purification, and types of unit operations used, and were reported to be in the ranges of 1–210 g N kg^{-1}, 1–150 g P kg^{-1}, 1–65 g K kg^{-1}, 5–170 g Ca kg^{-1}, and 2–94.5 g Mg kg^{-1} (Hansen and Chaney, 1984; Solis-Mejia *et al.*, 2012). Application of biosolids on agricultural and degraded lands is one of the most promising alternatives of disposal, because it offers the possibility of recycling plant nutrients and organic matter (García-Orenes *et al.*, 2005; Torri and Lavado, 2009a, b; Kowaljow *et al.*, 2010). This practise may also contribute to soil C sequestration, reducing greenhouse gas emissions (Haynes *et al.*, 2009; Tian *et al.*, 2009; Torri and Lavado, 2011; Torri *et al.*, 2014). However, biosolids may contain undesirable hazardous substances such as potentially toxic trace elements ranging from less than 1 to over 1 000 mg kg^{-1}, polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and dioxins (Abad *et al.*, 2005; Martínez *et al.*, 2007; Torri, 2009; Ahumada *et al.*, 2014; Jordán *et al.*, 2016). Consequently, biosolids have to be properly treated and disposed to prevent health risk and environmental contamination (Kroiss, 2004). Although to date experimental results indicate a low level of risk for crops or pastures (Torri and Lavado, 2009a, b; Cogger *et al.*, 2013a), application of biosolids onto non-agricultural land is usually preferred to avoid the risk of hazardous substances entering the food chain (Magesan and Wang, 2003; Athamenh *et al.*, 2015).

In the European Union, a global regulation on biosolid use in agriculture relies on the Water Framework Directive (2000/60/EC) (EC, 2000) and the subsequent Groundwater Directive (2006/118/EC) (EC, 2006), which have resumed all the previous specific Directives on bathing waters, sewages sludge, urban wastes and nitrates, and limit the potential recycle of any biosolids in agriculture to their impacts on surface water, groundwater, and atmosphere caused by excessive nutrient, organic and inorganic pollutants. While most organic pollutants can be degraded and excessive N may be volatilized during sludge treatment, trace elements are generally concentrated and may exceed the mandatory limits for sludge application to agricultural soils (CEC, 1986). Elevated contents of trace elements prevent the use of sludge as a soil amendment because of their negative impacts on soil microbial diversity and microbial activity (Renella *et al.*, 2007a; Gomes *et al.*, 2010).

In wastewater, P is mainly found as orthophosphates, usually linked to small amounts of organic P (Tran *et al.*, 2012). Phosphorus removal is performed by biological treatment or physiochemical precipitation. In both cases, the soluble forms of P are converted into a solid fraction, which can be an insoluble salt or microbial biomass (De-Bashan and Bashan, 2004). Physiochemical precipitation removes dissolved P phosphates by the addition of aluminium (Al), iron (Fe), or calcium (Ca) compounds (Lee and Lin, 2007). The reaction is probably a combination of surface adsorption onto metal hydroxides with chemical precipitation of the metal phosphate, producing low P concentrations in the liquid phase (Elliott and O'Connor, 2007). Biological P removal (BPR) process relies on the use of a specific group of bacteria that take up P in excess for their growth requirements (Chen *et al.*, 2013; Keating *et al.*, 2016). The excess of P is stored as intracellular granules of polyphosphate (Grady *et al.*, 2011), concentrating diluted P in waste-