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INSPIRATION bulletin

CL:AIRE's INSPIRATION bulletins describe practical aspects of research which have direct application to the management of contaminated soil or groundwater in an agricultural context. This bulletin describes the selection and assessment of materials for removing and recycling phosphorus to soil.

Indicators for the selection of filter media options for phosphorus recycling to agricultural soils

1. Introduction

The use of low-cost raw or waste filter media for the recovery of phosphorus (P) from water/wastewater streams (e.g. land drainage) and reuse in agricultural soils as a fertiliser may be an alternative to or complement inorganic fertilisers. This approach fits well with the "circular economy" concept (Figure 1).

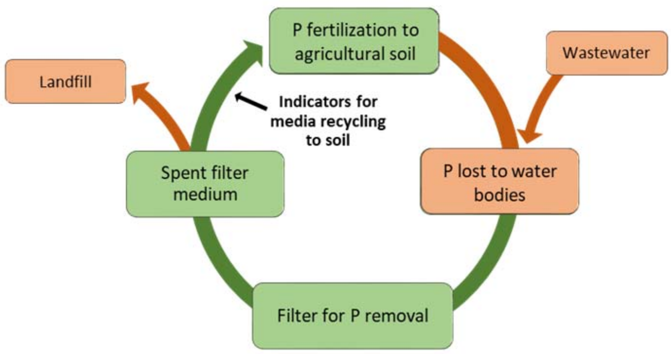

Figure 1: Circular economy in P spent filter media recycling to soil.

Such a solution may address water pollution problems, the disposal of large volumes of generated waste and global P depletion, while also producing materials suitable for agricultural use and reducing fertiliser costs. However, several technical issues and parameters must be considered before reusing a P-saturated material directly as a fertiliser replacement. The aim of this bulletin is to provide a general background to the materials that have been investigated for removing and recycling P to soil and important parameters/indicators to be taken into account when assessing such materials for use.

2. Classification of materials

Several materials (Fig. 2) have been used as filter media to remove P from water streams which could be recycled to soil as alternative P fertilisers. These materials are classified according to their source (naturally-occurring materials, processed materials or waste materials) and composition [high concentration of calcium (Ca), aluminium (Al), or iron (Fe)].

Source: Naturally-occurring materials like limestone, phosphate rock or iron-/aluminium-rich sand (Fig. 2a) are extracted from quarries but there are many other examples such as soil or seashells. Processed materials have undergone some transformation process, e.g. pelletised apatite (Fig. 2b), or lightweight aggregates (LECA, Filtralite P) and Polonite® (processed bedrock opoka, Fig. 2c), which have been commercially developed for P removal in, for example, constructed wetlands. Some waste materials that have been tested for this purpose include steel slag (Fig. 2d), which is generated from the steelmaking industry; concrete waste (Fig. 2e); and alum sludge (Fig. 2f), a common drinking water treatment waste material mainly composed of organic matter and aluminium sulphate used for coagulation (Zhao *et al.*, 2018).

Figure 2: Sample of materials used as filter media for P removal. [1] Troesch *et al.*, 2016. [2] Ecofiltration Nordic AB, 2017. [3] Yildirim *et al.*, 2011. [4] Wagih *et al.*, 2013.

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Inspiration

Composition: The Ca, Al or Fe content of the material is important in terms of P sequestration capacity. These in turn will dictate largely the plant available P content of the materials once saturated. For example, limestone, Polonite and concrete have a relatively high concentration of Ca, whereas water treatment residuals (WTRs) are generally Al-rich and some types of sand have a high concentration of Fe. The distribution and concentration of these elements in the media dictates the solubility that the adsorbed P will have and, therefore, determines how much P will be plant-available at a certain pH.

3. Indicators

A material must have good P sequestration capacity but after saturation be capable of releasing P to soil in a form that is plant available. Specifically, for a material to be efficient for P recycling, it first needs to work as an efficient filter medium to remove P. Important factors which contribute to this function are the P-removal capacity, removal capacity of other pollutants, hydraulic conductivity, life-time before P saturation and negative externalities (e.g. pollution swapping, contaminant leaching) (Ezzati *et al.*, 2019). Key indicators to recycle the P-saturated material as a fertiliser replacement are the following: total P concentration and P pools in the soil, plant response when the material is applied, additional benefits as a soil amendment, potential negative effects to the plant or environment and finally, its local availability.

Total P: The theoretical maximum concentration of P that a filter medium can adsorb is referred to as the adsorption maxima (Q_{max}). This value is widely reported for different materials and is obtained from experimental adsorption isotherms (Fig. 3) where the equilibrium concentration of P (C_e) is plotted against the adsorption capacity of the material (q_e), typically following a Langmuir isotherm.

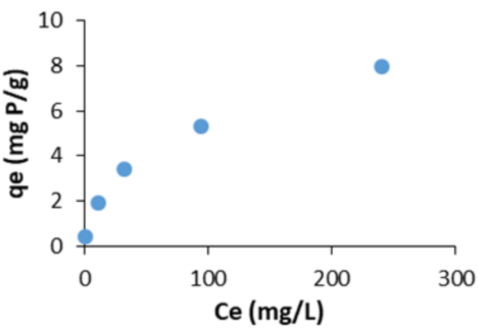

Figure 3: Alum sludge P adsorption isotherm (unpublished).

The Langmuir adsorption equation (Olsen & Watanabe, 1957), which assumes a monolayer adsorption process on a homogeneous surface, is linearised (Equation 1) to calculate Q_{max} and b (constant related to the bonding strength of P on the material). Another adsorption model commonly used is the Freundlich model, which represents a multilayer adsorption on a heterogeneous surface.

$$\frac{C_e}{q_e} = \frac{1}{Q_{max}} C_e + \frac{1}{Q_{max} b} \qquad \text{Equation 1}$$

Materials with a low Q_{max} could be discarded for direct reuse as P fertiliser. Some materials with a high Q_{max} are alum sludge [up to 23 g P/kg (Babatunde & Zhao, 2009)] and crushed concrete [6.88 g P/kg (Deng & Wheatley, 2018)]. However, Q_{max} generally depends on the solution pH, initial P concentration, source and particle size of the medium. Although the total P value is useful to compare among media, these other parameters should also be considered and the composition of P forms in the media should be assessed.

P pools: Inorganic phosphorus in the soil can be classified in four different levels of availability or pools. Pool 1 is immediately available in the soil solution, pool 2 is surface adsorbed and readily available, pool 3 is more strongly bonded and less available and pool 4 has very low availability because of strong bonds or precipitation (Johnston *et al.*, 2014). The plant-available P in a soil (pool 1 and 2) after applying fertiliser replacement materials is an indicator of the performance of the medium in an agronomic context. Although there is disagreement on which P extraction procedure is most closely related to the amount of P taken up by a plant (Brod *et al.*, 2015), some common extractants are ammonium lactate (Cucarella *et al.*, 2009), water and Morgan's solution (sodium acetate) (Teagasc, 2016). However, it is also important to assess the other P pools in a soil to predict the long-term performance and environmental risk of the media. The composition of the filter medium dictates the form of P that will be present in a soil, e.g. P-sorbing materials high in Al will provide low water-extractable P, thus reducing the risk of leaching or runoff (Agyin-Birikorang *et al.*, 2007), but also reducing the plant availability compared with Ca-bound P (Vohla *et al.*, 2011). The application of a P fertiliser has to consider that the amount of readily available P in the soil should be just enough to avoid limiting plant growth of the specific type of crop and the rest should be in less available pools.

Plant response: When P is the limiting nutrient and all other environmental conditions are optimal for plant growth, the plant response to a fertiliser replacement material can be reported as plant yield (dry biomass). Although only a few studies have conducted agronomic tests using P-saturated filter media as fertiliser replacement, positive results in plant yield have been found using P-saturated steel slag (Hylander & Simán, 2001), Polonite (Cucarella & Renman, 2009) and lightweight aggregates (Kvarnström *et al.*, 2004).

Benefits as soil amendment: Filter media used as soil amendments can improve the soil fertility or physicochemical properties in addition to providing nutrients. Calcium-rich media, such as Polonite (Cucarella *et al.*, 2009) and recycled concrete (Deng & Wheatley, 2018) can increase pH in acidic soils or water, acting as a liming agent in the soil. WTR has a high organic matter content and has been reported to improve the water-holding capacity and aeration of the soil (Zhao *et al.*, 2018).

Negative effects: Several studies have reported negative effects by mixing novel or waste media with soil. Soil Ca content can be increased when using P-saturated Polonite (Cucarella *et al.*, 2009) and liming agents (e.g. lime or $CaCO_3$) added at high rates (e.g. P-fertilisation rates), which can induce plant diseases, such as grey spec disease (Hylander & Simán, 2001). Also, the use of Al-rich adsorbents can induce Al toxicity (Zhao *et al.*, 2018). In addition, unwanted elements such as heavy metals may also be added and potentially leached to the soil. Steel slags have been reported to adsorb copper, zinc and nickel (Dimitrova & Mehanjiev, 2000), alum sludge has been used to remove arsenic from wastewater (Zhao *et* *al.*, 2015), and recycled concrete has been found to leach arsenic, chromium, lead, and selenium above the US drinking water standard (Chen *et al.*, 2013).

Availability and cost: Provided these filter media are readily available at a low cost their use could be widely adopted. Hence, waste media generated locally would be the preferred option. While WTR is generated in high volumes in water treatment facilities around the world (Dassanayake *et al.*, 2015), the availability of other materials may be limited to specific regions, e.g. Filtralite P is limited to the Nordic countries.

3. Conclusion

There are many filter media that can potentially be used for P recycling to a soil. However, even if some media have inherently a higher capacity for P adsorption, other characteristics must be considered when using them as a soil amendment. Therefore, more agronomic tests are needed to evaluate the positive and negative effects of these materials on soils and plants, and the cost-effectiveness of reusing filter media to agricultural soils in specific cases should be assessed.

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