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Review

Evaluation of the fertiliser replacement value of phosphorus-saturated filter media

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ABSTRACT

The use of filter media to adsorb phosphorus (P) from nutrient-rich waters is an effective, simple and low-cost method to recover and reuse P as an inorganic fertiliser replacement. Although it is assumed that the saturated filter media can be applied to cropland as a safe fertiliser replacement, there is presently a lack of information on the fertiliser replacement value (FRV) of such products and their negative effects on plants and soil. Therefore, the aims of this paper were to evaluate the (1) P removal capacity and plant response to soil application of waste media from three sectors (industry, agriculture, and construction and demolition), and natural and synthetic materials (2) potentially confounding risks arising from the reuse of media as a fertiliser replacement, and (3) factors affecting their fertilising efficiency once applied to soil. The predominant factors affecting the FRV of P-saturated media were their adsorption capacity and chemical composition, soil pH, and composition of water used for saturation. Some measures to overcome the negative impacts of the land application of P-saturated media include selecting the most appropriate soil-filter material combinations, the use of P solubilising microorganisms, and mixing with manure before land application. Despite confounding factors and a lack of information on the performance of some media under comparable study conditions, this study found that there is a significant potential for P-saturated filter media to partially replace the use of P mineral fertilisers and aid in the attainment of a "circular economy" in agriculture.

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1. Introduction

The recovery and reuse of phosphorus (P) is a main requirement towards a circular bioeconomy (Jarvie et al., 2019), which aims at safeguarding future rock phosphate resources and achieving planetary P sustainability goals (Withers et al., 2015; Carraresi et al., 2018). The use of filter media to adsorb P from contaminated water streams is an effective method to recover P, due to its simplicity and low cost (Vohla et al., 2011), and exploring the reuse of P-loaded media as fertilisers after direct soil application has been advised to reduce pressure on the limited worldwide P reserves (Bacelo et al., 2020; Wendling et al., 2013).

Waste materials are especially attractive media in filtration systems for environmental and economic reasons. Turning waste into resource is a priority for waste management policies in the European Union (EU), where only 34% of the 2.5 billion tons of waste produced annually is recycled and the rest is either landfilled or burned (Eurostat, 2019a). Phosphorus adsorption media have been reviewed extensively and special focus has been given to the revalorisation of waste materials, and the use of low-cost and locally-available materials as filter media (Bacelo et al., 2020; Ballantine and Tanner, 2010; Ezzati et al., 2019; Grace et al., 2016; Penn et al, 2007, 2017; Vohla et al., 2011; Wendling et al., 2013). These materials can be classified into five categories: (1) industrial waste (2) agricultural waste (3) construction and demolition (C&D) waste (4) natural materials, and (5) synthetic materials (Table 1).

A central paradox exists concerning the effective reuse of natural or waste materials as fertilisers: for a material to be used successfully as a filter medium for P removal, it should have the capacity to adsorb and immobilise P, preventing further loss to the water stream; however, this characteristic may make it unsuitable for use as a fertiliser. Although some reports (Hylander et al., 2006; Bird and Drizo, 2009; Kõiv et al., 2012) have found that P-saturated media with a high P adsorption capacity (e.g. steel slag, Polonite and hydrated oil shale ash) can replace inorganic fertilisers, the amount that has to be applied to the soil to substitute an inorganic fertiliser would be unpractical at large-scale since only a small fraction of P is plant available. The adsorption capacity of a filter medium does not indicate how well it will perform as a fertiliser when applied to the soil (Wendling et al., 2013), but the fertiliser replacement value (FRV) would provide more information about how a material performs compared to a mineral fertiliser.

There are many reports on the removal of P with a range of filter materials, but most of these studies focus on the adsorption capacity of the media and do not address the issue of the disposal/reuse of these materials after saturation (Barca et al., 2012; Cusack et al., 2019; Guan et al., 2009; Kang et al., 2017; Sønderup et al., 2014; Xiong and Mahmood, 2010). Some studies mention their suitability as P fertilisers based on their P concentration post-sorption or after desorption tests (Huang et al., 2019; Jellali et al., 2011; Liu et al., 2019; Shepherd et al., 2016), but relatively few studies have evaluated their FRV in pot or field agronomical studies (Tables 2–6). Natural materials, such as sand and limestone, industrial waste materials, such as water treatment residuals, blast furnace slag and steel slag, and synthetic materials, such as layered double hydroxides, have been examined for their P adsorption capacity and for plant and soil response to the land application P-loaded filter media. This is commonly reported as plant biomass, plant P content, or soil available P (Bird and Drizo, 2009; Hylander et al., 2006; Litaor et al., 2019; Qiao et al., 2019).

Although there is potential for land application and P recycling to the soil, the success of each specific case will depend on the combination of characteristics of the media and soil (Hylander et al., 2006; Hylander and Simán, 2006), as well as the wastewater used for saturation (Zohar et al., 2017). Using some of these locally-sourced and low-cost materials for P recycling would make the use of P filtering systems more economically attractive and further aid in the attainment of a circular economy, not only of P, but also of these waste materials. Therefore, the aims of this review are to: (1) examine the P removal capacity and FRV of P-loaded filter media by comparing differences in plant shoot biomass, plant shoot P content and soil available P with mineral P fertilisers (2) compare the factors that affect their FRV, and (3) provide an insight to different methods that have been tested to overcome difficulties in their use as P fertilisers.

2. Methodology

The methodology followed during this review is shown in Fig. 1. The main steps followed were, first, a literature search on the reuse of P-saturated filter media in agriculture; second, refining of papers obtained using specific inclusion parameters; third, extraction of relevant information from these papers, and finally, a calculation of the difference in measurable outcomes (e.g. plant shoot biomass or P content, soil available P, or soil pH) following the reuse of P-saturated media or mineral fertiliser.

Table 1
Availability of materials in five classifications (construction and demolition, agriculture, industry, natural and synthetic) for phosphorus removal.

Classification	Material	Current use/disposal	Pre-treatment for P removal	Raw material availability in EU	Reference
Industrial waste	Water treatment residuals	Landfill Land application	Air-dried and ground	Generated/recycled (x 10^3 tonnes): 131/0 (UK 2013), 328/322 (Netherlands 2014), 78/0 (Belgium 2014), 9/8 (Denmark 2015)	Turner et al. (2019); Yang et al. (2006); Zhao et al. (2018)
	Steel slag	Road construction Metallurgical use Landfill (14%)	Crushed	EU: 18.4 Mt (2016)	Euroslag (2019)
	Ochre	Stored or landfilled	Used raw, pelletized or after acid treatment	UK: 4,500 t of dry ochre year^{-1}	Fenton et al. (2009); Sapsford et al. (2015)
	Coal fly ash	Concrete additions Other construction applications	Used raw or chemically or thermically activated for increased P adsorption capacity	85% of ash generated in coal combustion processes 780 Mt year^{-1} worldwide	Grace et al. (2016)
	Wollastonite tailings	Waste material with high P adsorption	Waste from pure wollastonite production	Abundant in northern New York State, USA	Brooks et al. (2000)
	Oil shale ash	Cement or brick manufacture	Used raw after hydration	45–48 kg per 100 kg of shale processed Estonia: 22 Mt of oil shale and oil sand year^{-1}	Eurostat (2019b); Smadi and Haddad (2003)
	Bauxite residue	Bauxite residue storage areas Road construction material Drainage layer Only 2–3% recycled	Washed and used raw or partially neutralised	Estimated 3,000 Mt accumulated by 2010 (worldwide) EU: 2 Mt of aluminium year^{-1}	European Aluminium (2015); Evans (2016)
Agricultural waste	Biochar	Soil amendment	Mixed with other compounds for increased P adsorption	Produced from various biomass waste materials depending on local availability	Chen et al. (2017)
	Coconut shell	Bowls and utensils in developing countries Water treatment (activated carbon)	Pyrolysis for activated carbon production	Available in coastal tropical countries EU (2017): 1,858 t	Food and Agriculture Organization (2019); Grace et al. (2016)
Construction and demolition waste	Crushed glass	Mostly to landfill	Crushed	Germany (2007): 2.6% of C&D including other waste products Flanders (2007): 1.89% of C&D	European Commission DG ENV (2011)
	Crushed concrete	Recycled as aggregate in some countries Landfill	Crushed	EU-27: 320–380 Mt year^{-1}	European Commission DG ENV (2011); Grace et al. (2016)
	Masonry waste	Aggregate for concrete production Replaces sand, stones, rocks to fill roads	Crushed	No data available in EU-27 Total C&D waste is 540 Mt year^{-1} (2008)	Grace et al. (2016)
Natural materials	Limestone	Construction Soil conditioner	Crushed	Europe (2018): 199 Mt	Eurostat (2019b)
	Opoka	Wastewater treatment	Calcinated	Quarried from Poland, Lithuania, Ukraine and Russia	Brogowski and Renman (2004)
	Sand	Construction, wastewater treatment		Highly variable, depends on the type of sand	
	Soil				
	Clay	Construction	Heating and/or lime addition for P removal	Highly available material	LECA (2019)
	Dolomite	Soil conditioner	Crushed	Europe (2018): 29 Mt	Eurostat (2019b); Huang et al. (2019)
	Zeolite	Catalysis, adsorbent, ion exchange	Surfactant modified for P removal	Abundant naturally and produced industrially	Guaya et al. (2018); Misaelides (2011); Wang and Peng (2010)
Synthetic materials	Filtra P	P adsorbent in wastewater treatment plants	Commercial product		Cucarella et al. (2007)
	Polonite	P adsorbent in wastewater treatment plants	Commercial product	Sold by Ecofiltration (Poland and Sweden)	Cucarella et al. (2009)
	Expanded clay aggregates	P adsorbent in wastewater treatment plants or wetlands	Commercial product	Manufactured by Leca Norge AS (Norway)	Filtralite (2019)
	Metal-layered double hydroxides	P removal	Synthesised in the laboratory	Experimental material	Everaert et al. (2016); Qiao et al. (2019)
	Fe (III)–Polysaccharide hydrogel beads	P removal	Synthesised in the laboratory	Experimental material	Karunarathna et al. (2019)

Table 2
P fertiliser efficiency evaluation of P-loaded industrial waste.

Material	P-loaded medium			Experimental set-up			Experiment results				Reference
	Water used for saturation	Total P (mg P g^{-1})	Available P[†] (% of total P)	Application rate (mg P kg^{-1} soil)	Plant	Experimental duration	Shoot dry biomass	Shoot P content	Soil available P[†] (mg P kg^{-1})	Soil pH (in H$_2$O)	
							% increase versus mineral fertiliser treatment				
Pot studies											
Water treatment residuals	Dairy wastewater	10	7 %[d]	54 *	Romaine lettuce (*Lactuca sativa* L.)	60 days	10.3 %[j]	- 32.1%	25[d] (92%)	NA	Litaor et al. (2019)
Fine crystalline blast furnace slag	Synthetic P solution	0.62[q]	NA	7.1	Barley	47 days	32%	−3%	4.65 (0%)	6.4 (12%)	Hylander and Simán (2001)
				70.6			3%		49.55 (256%)	7.4 (30%)	
		0.394[q]		7.1			41%	3%	6.19 (33%)	6.1 (7%)	
				70.6			13%		69.68 (400%)	7 (23%)	
Coarse crystalline blast furnace slag		0.524[q]		7.1			45%	8%	4.65 (0%)	6.1 (7%)	
				70.6			2%		57.29 (311%)	7 (23%)	
		1.268[q]		7.1			18%	0%	7.74 (67%)	6 (5%)	
				70.6			2%	−4%	57.29 (311%)	6.8 (19%)	
Coarse amorphous blast furnace slag		0.99[q]		7.1			−5%	8%	7.74 (67%)	5.8 (2%)	
				70.6			−16%		85.17 (511%)	6.6 (16%)	
		1.75[q]		7.1			14%	5%	6.19 (33%)	5.7 (0%)	
				70.6			−8%		58.84 (322%)	6.2 (9%)	
Amorphous blast furnace	Municipal wastewater	0.26	NA	8.3	Barley	70 days	−13%	NA	NA	5.49 (3%)	Hylander et al. (2006)
Crystalline blast furnace slag		0.3					−11%			5.72 (8%)	
Electric arc furnace slag	Dairy wastewater	1.09[f]	62 %[a]	4.2 *	Alfalfa (*Medicago sativa*)	10 weeks	0%	NA	NA	NA	Bird and Drizo (2009)
				25.4 *			−76%				
Ochre	Synthetic P solution	22.78	4%[b]	25.9[b]*	Barley	3–4 months	11%	17%	11[b] (175%)	6 (9%)	Dobbie et al. (2005)
				193.6[b]*	Birch	7–8 months	14%	NA	NA	NA	
					Spruce		10%	NA	NA	NA	
CaO–MgO hybrid carbon composite from sawdust	Swine slaughterhouse wastewater	22.37[f]	NA	223.7	Chinese brassica	21 days	204.2 %[m]	NA	NA	NA	Li et al. (2018)
Field studies											
Water treatment residuals	Synthetic P solution	0	NA	0	Sorghum-sudan	83 days	24%	NA	NA	NA	Hyde and Morris (2004)
		4.9[f]		8.2 *			−38%				
		14.6[f]		24.5 *			−75%				
		60.7[f]		104.5 *			6%				
Ochre	Synthetic P solution	22.78	4% b	9.2[b]*	Perennial ryegrass	3–4 months	7%	NA	NA	5.6 (2%)	Dobbie et al. (2005)
				25.9[b]*	Barley		12% grain			5.9 (7%)	

[†] as ammonium lactate extractable P; * estimated; [a] DRP; [b] 2.5% acetic acid extractable P; [c] mg M3-P kg^{-1}; [d] Olsen P; [f] mg P taken up during adsorption; [h] Truog-phosphate; [j] fresh biomass; [k] wet soil; [l] acid hydrolysable P; [m] against no fertiliser control; [q] extracted by 7 M HNO$_3$; NA not available.

A detailed, state-of-the-art search of P-saturated filter media reuse in agriculture in peer-reviewed papers from indexed journals from the last 20 years was completed using the following keywords: agriculture, adsorption, amendment, available phosphorus, fertiliser, fertiliser replacement value, filter medium, phosphorus, recovery, recycling, reuse, saturated, and soil. Various combinations and derivations of the keywords were used (for example: adsorb, adsorbed, or adsorption). Additionally, the materials used as filter media were also included in the literature search and further references cited in those papers or citing those papers were examined.

The databases searched were: Alliance of Crop, Soil, and Environmental Science Societies (ACSESS), American Chemical Society (ACS), Google Scholar, ScienceDirect, Scopus, and Web of Science. From the initial search, the list of references was reduced to consider only original research with the following as one of its objectives: testing the reuse of P-loaded filter materials as P fertilisers in the laboratory, greenhouse, or field.

As a result of these search criteria, 41 peer-reviewed journal papers were selected, from which over 50% were published in the last 5 years and 75% in the last 10 years. The authors reported their findings using a wide range of soil and plant parameters. To allow comparison, only the studies that evaluated plant shoot biomass and/or plant shoot P content from a P-saturated filter medium fertiliser against a control (mineral P fertiliser or no P fertiliser) were selected for analysis (20 papers). Plant shoot biomass and plant shoot P content were the most common indicators of

Table 3
P fertiliser efficiency evaluation of P-loaded agricultural and C&D waste in pot studies.

Material	P-loaded medium			Experimental set-up			Experiment results				Reference
	Water used for saturation	Total P (mg P g^{-1})	Available P† (% of total P)	Application rate (mg P kg^{-1} soil)	Plant	Experimental duration	Shoot dry biomass	Shoot P content	Soil available P† (mg P kg^{-1})	Soil pH (in H_2O)	
							% increase versus mineral fertiliser treatment				
Pot studies											
MgO-Cow dung biochar	Synthetic P solution	NA	NA	NA	Lettuce	60 days	41.9 %[m]	75.8 %[m]	27.95[l] (966 %[m])	6.86 (17.7 %[m])	Chen et al. (2018)
Mg-impregnated sugarcane biochar	Synthetic P solution	NA	NA	NA	Ryegrass	21 days	206.3 %[m]	NA	NA	NA	Li et al. (2016)
Porous glass with crushed shells	Synthetic P solution	0.646[f]	NA	129.2	Tomato (*Lycopersium esculentum* L.)	44 days	−90%	NA	88.6[h] (9.8%)	7.2 (10.8%)	Nakazawa et al. (2006)

† as ammonium lactate extractable P; * estimated; [a] DRP; [b] 2.5% acetic acid extractable P; [c] mg M3-P kg^{-1}; [d] Olsen P; [f] mg P taken up during adsorption; [h] Truog-phosphate; [k] wet soil; [l] acid hydrolysable P; [m] against no fertiliser control; [q] extracted by 7 M HNO_3; NA not available.

Table 4
P fertiliser efficiency evaluation of P-loaded natural materials.

Material	P-loaded medium			Experimental set-up			Experiment results				Reference
	Water used for saturation	Total P (mg P g^{-1})	Available P† (% of total P)	Application rate (mg P kg^{-1} soil)	Plant	Experimental duration	Shoot dry biomass	Shoot P content	Soil available P† (mg P kg^{-1})	Soil pH (in H_2O)	
							% increase versus mineral fertiliser treatment				
Pot studies											
Limestone	Municipal wastewater	0.42	NA	8.3	Barley	70 days	−52%	NA	NA	6.38 (20%)	Hylander et al. (2006)
Opoka		0.31					−39%			6.00 (13%)	
Sand		0.46					−35%			5.33 (0%)	
Natural opoka	Synthetic P solution	1.383[q]	NA	7.1	Barley	47 days	−18%	3%	6.19 (33%)	6.2 (9%)	Hylander and Simán (2001)
				70.6			−35%	−45%	52.65 (278%)	7.1 (25%)	
Limestone	Synthetic P solution	0.781[q]		7.1			−45%	3%	6.19 (33%)	7.1 (25%)	
				70.6			−100%	−48%	NA	NA	
Burned lime	Synthetic P solution	2.29[q]		7.1			−27%	−18%	6.19 (33%)	7.1 (25%)	
				70.6			−89%	NA	77.43 (456%)	8.7 (53%)	
Soil from spodic B horizon	Synthetic P solution	1.568[q]		7.1			−27%	5%	4.65 (0%)	5.7 (0%)	
				70.6			−21%	−51%	9.29 (−33%)	5.8 (2%)	
Iron-rich fine sand	Domestic wastewater	0.426	15%	20[f]	Italian rye grass (*Lolium Multiflorum* Italicum)	55 days	−7%	−5%	NA	NA	Kvarnström et al. (2004)
Sand and gravel		0.366	29%				−5%	−7%			
Sand		0.558	23%				−5%	−11%			

† as ammonium lactate extractable P; * estimated; [a] DRP; [b] 2.5% acetic acid extractable P; [c] mg M3-P kg^{-1}; [d] Olsen P; [f] mg P taken up during adsorption; [h] Truog-phosphate; [k] wet soil; [l] acid hydrolysable P; [m] against no fertiliser control; [q] extracted by 7 M HNO_3; NA not available.

fertilisation treatment success. The following information was extracted from these papers using tables or text, when available, or from plots using Web Plot Digitizer (https://apps.automeris.io/wpd/): P sorption material used, type of water used for P loading, post-sorption total and available P concentration in the filter medium and maximum adsorption capacity, application rate, model plant used, plant and soil physicochemical characteristics as fertilisation experiment results (plant shoot biomass, plant shoot P content, soil available P and soil pH), and negative side effects such as phytotoxicity.

Only few media have been tested two (water treatment residuals, ochre, magnesium (Mg(-impregnated biochar, limestone, opoka, LECA, Filtra P) or more times (steel slag, sand, Polonite, layered double hydroxides) under the above described criteria and the experimental conditions differ (medium pre-treatment, water used for saturation, application rate, filter medium total P, model plant, experimental duration), so the results cannot be quantitatively compared among experiments.

To homogenise the application rate, it was converted from kg P ha^{-1} to mg P kg^{-1} soil assuming a 30 cm depth unless more information about the pot or field was available and the soil density from each soil type was obtained from Batjes (1997) or 1.3 g cm^{-1}

Table 5
P fertiliser efficiency evaluation of P-loaded synthetic materials.

Material	P-loaded medium			Experimental set-up			Experiment results				Reference
	Water used for saturation	Total P (mg P g^{-1})	Available $P^{\dagger}$ (% of total P)	Application rate (mg P kg^{-1} soil)	Plant	Experimental duration	Shoot dry biomass	Shoot P content	Soil available $P^{\dagger}$ (mg P kg^{-1})	Soil pH (in H_2O)	
							% increase versus mineral fertiliser treatment				
Pot studies											
Filtra P	Synthetic P solution	0.714	3%	4.3^{k}	Barley	64 days	−2%	18% in spikes	13.65 (7%)	7.24 (6%)	Cucarella et al. (2007)
Polonite		1.862	1%	10.2^{k}			−5%	2% in spikes	13.88 (9%)	7.34 (7%)	
Wollastonite		0.254	6%	2.0^{k}			−1%	10% in spikes	12.89 (1%)	7.18 (5%)	
Filtra P	Synthetic P solution	0.714	3%	4.3^{k}	Perennial ryegrass (*Lolium multiflorum*)	50 days	4%	59%	6.32 (4%)	5.52 (22%)	Cucarella et al. (2008)
Polonite		1.862	1%	10.2^{k}			3%	47%	6.48 (7%)	5.12 (14%)	
Wollastonite		0.254	6%	1.7^{k}			1%	11%	6.27 (3%)	5.02 (11%)	
Polonite	Municipal wastewater	1.02	NA	8.3	Barley	70 days	−33%	NA	NA	5.59 (5%)	Hylander et al. (2006)
		1.64					−28%			5.41 (2%)	
		0.47					−24%			5.98 (12%)	
Burned opoka	Synthetic P solution	1.322^{q}	NA	7.1	Barley	47 days	−18%	−3%	7.74 (67%)	6.2 (9%)	Hylander and Simán (2001)
				70.6			−58%	−32%	55.75 (300%)	7.4 (30%)	
LECA		0.498^{q}		7.1			−27%	0%	6.19 (33%)	5.8 (2%)	
				70.6			−16%	- 37%	10.84 (−22%)	6.1 (7%)	
Filtralite P					Italian ryegrass	3 yields					Jenssen et al. (2010)
	Synthetic P solution	9.03	52%	100				−33%			
Light Weight Aggregate (LECA)	Domestic wastewater	0.36	61%	20^{f}	Italian rye grass (*Lolium Multiflorum* Italicum)	55 days	0%	7%	NA	NA	Kvarnström et al. (2004)
Clay-based layered double hydroxides	NA	0	NA	0	Barley	21 days	0%	NA	NA	NA	Kong et al. (2019)
		22		55			45%				
		44		110			29%				
		66		165			65%				
		88		220			35%				
Mg—Al Layered Double Hydroxides	Synthetic P solution	40	NA	10 at pH 4.2	Barley	17 days	NA	33%	NA	4.3 (0%)	Everaert et al. (2016)
				300 at pH 4.2				292%		6 (40%)	
				10 at pH 7				0%		NA	
				300 at pH 7				−52%		NA	
Magnetic Fe3O4/Zn—Al—Fe—La layered double hydroxides	Synthetic P solution	260	NA	140 *	Soybean (*Glycine max*)	4 weeks	10%	NA	NA	6.5 (14%)	Qiao et al. (2019)
Hydrogel beads	Synthetic P solution	0.487	NA	97.44	Kale (*Brassica oleracea*)	6 weeks	30 $\%^{m}$	NA	NA	NA	Karunarathna et al. (2019)
Field study											
Polonite	Domestic wastewater	1.5	18%	5.2 *	Established grass cover (Gladiolo-Agrostietum)	70 days	4%	2%	36.9 (24%)	5.79 (8%)	Cucarella et al. (2009)

[†] as ammonium lactate extractable P; * estimated; [a] DRP; [b] 2.5% acetic acid extractable P; [c] mg M3-P kg^{-1}; [d] Olsen P; [f] mg P taken up during adsorption; [h] Truog-phosphate; [k] wet soil; [l] acid hydrolysable P; [m] against no fertiliser control; [q] extracted by 7 M HNO_3; NA not available.

was assumed. To compare the results among experiments, a percent increase in experiment results for each parameter *x* (plant shoot biomass, plant shoot P content, soil available P, or soil pH) was calculated (Eqn. (1)) comparing the P-saturated filter medium (PFM) result against the mineral P fertiliser (minP) result (or against no P fertiliser result):

$$\%\ increase_x = \frac{x_{PFM} - x_{minP}}{x_{minP}} \times 100\% \qquad \text{Eqn.1}$$

As such, positive increase values represent an increase in the

Table 6
Factors affecting efficacy of recycled P filter media as a fertiliser.

Factors	Possible effects	Consequences	Measures to overcome negative impacts
P adsorption capacity of the media			
- Low adsorption capacity	Mostly organic P removed by physical filtering instead of chemical adsorption. (sand[1])	Lower short term plant availability of P[1]	Treatment to increase adsorption capacity for example by incorporating P sorbing metals[2]
	Low P content in the medium after saturation	Lower yield/amendment ratio[3]	
- High adsorption capacity	Al-rich media act as sink of P in the soil if not completely saturated (WTR[4,5])	P deficiency[5]	Amend with additional P fertiliser[5]
	High P content in the medium after saturation	Highest yield/amendment ratio[3]	NA
Chemical composition of the media			
- High content of heavy metals	Mobilisation of heavy metals in soil[6] (LECA)[7]	Heavy metal cycling in the human food chain[8]	Follow heavy metal application limits (similar to biosolids[9]) Application to forestry land instead of agricultural land[8]
- High content of P-sorbing metals (Ca, Mg, Al, Fe)	Formation of insoluble P minerals[10,11,12]	Reduced plant yield[10,13]	Use of P solubilising microorganisms (tried with fly ash, slag and dolomite)[14,15,16,17] Mixing with manure produces organic acids and chelates during its decomposition which mobilises Ca, Al and Fe forms of P[18]
- Low content of P-sorbing metals (Ca, Mg, Al, Fe)	Material acts as a physical filter and removes suspended solids only, not soluble P[1]	Low supply of inorganic P[1]	Treatment to increase adsorption capacity for example by incorporating P sorbing metals[2]
- High content of Ca	Increase in soil pH[1,10]	Decreased availability of other plant nutrients like Mn[10]	Application only in acidic soils[1]
		Worsening of grey speck disease[1,10]	
		Beneficial liming effect when used on acidic soils[3,19]	NA
	Increase in soil salinity[20]	Decreased seed germination rate[20]	Reduce application rate
	Formation of poorly soluble or insoluble Ca—P minerals[12]	Low plant yield compared to a mineral fertiliser[13]	Use of P solubilising microorganisms to increase P availability[14,15]
	Slow release of P[21]	Prevents P losses in runoff or leaching[21]	NA
- High content of Mg	Slow release of P[21,22]	Prevents P losses in runoff or leaching[21]	NA
	Increase in soil pH (Mg-laden biochar[23])	Beneficial liming effect on acidic soils[23]	NA
- High content of Al	Aluminium toxicity in acidic soil[24] and to aquatic organisms[25]	Hinders plant growth	Application to soils with pH > 5.2[26,27]
	Formation of insoluble Al—P minerals[11]	Induction of P deficiency[24] and reduced plant yield (podsol and LECA)[10]	Use of P solubilising microorganisms to increase P availability[14]
- High content of Fe	Formation of insoluble Fe—P minerals[10]	P deficiency and reduced plant yield (podsol and LECA)[10]	Use of P solubilising microorganisms to increase P availability[14,15]
- Presence of other beneficial elements	High content of Si improves soil structure[3]		NA
	High content of Mn (Wollastonite)[3]: Supply of plant nutrient		
Soil pH			
- Alkaline pH	Increased P availability when Al-rich media applied compared to acid soils (alum sludge[27])	Plant yield increased when P is limiting nutrient	NA
	Further increase in soil pH when high pH media used[1,10]	Decreased availability of micronutrients (Mn, Mg, B[28]) and worsening effects of grey speck disease[1,10]	Avoid use of high pH media on high pH soil
- Acidic pH	Al toxicity possible at pH < 5.2 when Al-rich media used[24]	Hindered plant growth	Mix in lime or gypsum to increase pH prior to Al based-media application
	Beneficial increase in soil pH when high pH media used[3,19]	Liming effect that increases nutrient availability of improves plant yield[3,19,28]	NA
Composition of water used for saturation			
- Low P concentration	Lower adsorption capacity and lower accumulation of P (ex. Cr(VI) filter[29])	Low potential for P recycling[30]	Avoid using solution with very low P concentration[30]
- Low organic matter content	Lower P desorption capacity (WTR)[31]	Higher P content but lower availability of P in the soil[31]	Use of P solubilising microorganisms or mixing with manure post sorption
	Higher P removal capacity (WTR)[32]		
- High organic matter content	Reduced P sorption capacity, but P more loosely bound[31,32]	Higher availability of P in the soil[31,32]	NA
- High concentration of heavy metals	Retention of heavy metals by filter media[33] and mobilisation in soil[6] (LECA)[7]	Heavy metal cycling in the human food chain[8]	Restrict land application of filter media only from low heavy metal water
- Presence of pathogens	Possible transfer of pathogens to the soil[34]	Risk to public health and ecosystem[35]	Elimination of pathogens with similar treatments as for biosolids[9]

NA means not applicable. References: [1] Hylander and Simán (2006), [2] James et al. (1992), [3] Cucarella et al. (2008), [4] Brennan et al. (2019), [5] Hyde and Morris (2004), [6] Harikishore Kumar Reddy et al. (2017), [7] Paruch et al. (2007), [8] Cheuyglintase et al. (2018), [9] Fehily Timoney and Company (2009), [10] Hylander and Simán (2001), [11] Agyin-Birikorang and O'Connor (2007), [12] Asuman Korkusuz et al. (2007), [13] Cucarella et al. (2007), [14] Marhual et al. (2011), [15] Lukashe et al. (2019), [16] Gaind and Gaur (2002), [17] Piol et al. (2019), [18] Urvashi et al. (2007), [19] Adiloglu and Adiloglu (2009), [20] Courtney et al. (2009), [21] Huang et al. (2019), [22] Wang et al. (2015), [23] Chen et al. (2018), [24] Codling et al. (2007), [25] George et al. (1995), [26] Ippolito et al. (2011), [27] Litaor et al. (2019), [28] Teagasc (2016), [29] Baral et al. (2009), [30] Rittmann et al. (2011), [31] Zohar et al. (2017), [32] Zohar et al. (2018), [33] Renman et al. (2009), [34] Jenssen et al. (2010), [35] Liu (2016).

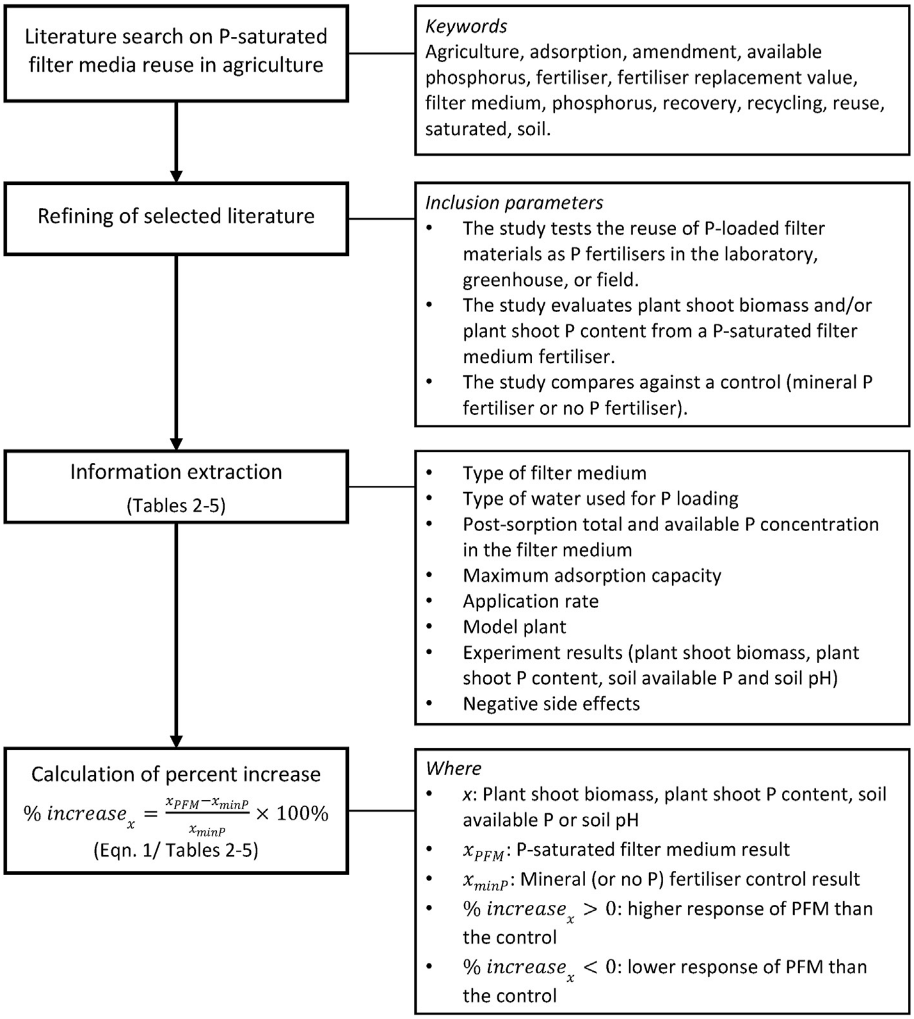

Fig. 1. Methodology flowchart.

given parameter against a mineral fertiliser and negative values represent a decrease against a mineral fertiliser control.

3. The FRV of P-saturated filter media

Materials with potential for P adsorption can be used with minimal pre-treatment or enhanced to increase their P sorption capacity. For the purpose of this paper, industrial waste comprises all materials generated as a by-product or waste from industrial activities such as water treatment, manufacture, mining, metallurgical industry, and energy production. Agricultural waste is defined as all biomass or animal-derived waste generated during this activity, which has been processed or modified for improved P removal. According to the EU classification (European Commission, 2019), C&D waste includes materials like concrete, bricks, wood, glass, metals and plastic that are generated during the construction and demolition of buildings and civil infrastructure. Materials classified as natural materials are those that are present in nature and are not a by-product or waste of another activity which can be used as they are, or have been processed or modified for improved P removal. Finally, in this paper, synthetic materials are those that are specially manufactured for P removal in water streams.

Table 1 shows different waste, natural and synthetic materials in the categories described above, the pre-treatment they need for use as filter media, and the availability of raw materials in the EU before processing for P adsorption.

Many of these materials are still disposed in landfills or special storage areas (glass, concrete, ochre, bauxite), but others are at least partially reused in the construction industry (fly ash, oil shale ash, steel slag) or as soil conditioners (biochar, limestone). The costs of pre-treatment of the materials for P removal are also variable. Some materials require relatively low-cost pre-treatments like drying and crushing (glass, concrete, dolomite), but others have to undergo thermal or chemical treatments to enhance their ability to remove P, which could be expensive at large scales. Regarding the generation of these materials in the EU, concrete and most industrial waste materials like fly ash, bauxite, steel slag and water treatment residuals (WTR), are potentially good options for P adsorption due to their high availability across the EU.

All the materials in Table 1 have had positive results for P removal. Most of these materials remove orthophosphates (as $H_2PO_4^-$, HPO_4^{2-} or PO_4^{3-} depending on the solution pH) from the water influent solution by a combination of physical and chemical sorption processes (Chen et al., 2018; Everaert et al., 2016; Kong et al., 2019). The most commonly cited adsorption mechanisms are precipitation to calcium (Ca), aluminium (Al), iron (Fe) or Mg oxides and hydroxides, anion exchange, electrostatic attraction, inner pore diffusion, and complexation (Chen et al., 2018; Cucarella and Renman, 2009; Everaert et al., 2016; Hyde and Morris, 2004; Kong et al., 2019).

However, their FRV differs because of different parameters such as the type of P bond to the material (e.g. Al or Ca-bonds), the amount of P applied, the composition of the wastewater used for saturation of the media, and the soil pH, among others. The types of materials that have been used for P removal and their results as fertiliser replacements in plant trials are evaluated in this section.

3.1. Industrial waste

3.1.1. Water treatment residual

Water treatment residual is a residue from the coagulation and removal of solids from drinking water treatment plants (Bugbee and Frink, 1985). It is commonly generated by adding aluminium sulphate (alum) and an organic polymer co-coagulant to water, which then coagulate the solid contaminants present in the water that are later removed by decantation. It is produced in large volumes and is mainly disposed in landfills (Table 1). However, as it contains P-binding elements such as Al, Fe and Ca, its reuse primarily as P adsorbent material has been extensively studied (Dassanayake et al., 2015). The reuse of alum sludge is advantageous, since it can be used in liquid form as it is generated from the drinking water treatment process or after a dewatering and drying pre-treatment, and its maximum adsorption capacity can be very high, ranging between 4 and 23 mg P g^{-1} (Babatunde et al., 2009; Bai et al., 2014; Hou et al., 2018; Yang et al., 2008). After saturation and given the high concentration of P in the medium, the alum sludge could potentially be applied to the soil as a P fertiliser.

The adsorption and plant-availability of P in WTR depend on its chemical composition and physical attributes (Bai et al., 2014; Hou et al., 2018). Bai et al. (2014) identified the strongest correlation between P adsorption and Al concentration, but other parameters were also correlated such as surface area, Fe concentration, organic matter, and pH. Hou et al. (2018) found that most of the P removed was bound to Ca, which is more available to plants, instead of Al/Fe-bound P, which is less available. However, the main components in WTR can be either Al, Fe or Ca, depending on the type and dosage of coagulant materials used (Bai et al., 2014). The presence of other coagulants in the water treatment process, such as polymeric coagulants, and the P saturation level attained in WTR also affects its adsorption and desorption potential. Hyde and Morris (2004) hypothesised that P formed a strong covalent bond with Fe when saturating an orthophosphate solution with Fe-based WTR at low P saturation levels, but at higher saturation levels, P formed weaker electrostatic bonds with the cationic polymer (also used in the coagulation process). Therefore, more P than expected was desorbed from the alum sludge at higher saturation levels and it was concluded that the presence of the cationic polymer was beneficial for the agricultural reuse of P-saturated WTR.

The performance of WTR as a fertiliser, shown in Table 2, is also affected by the type of wastewater used for P removal and the soil pH (Zohar et al., 2017). WTR mixed with a wastewater stream high in organic matter had more P desorption compared to WTR mixed with inorganic P only, possibly due to a weaker P adsorption in the presence of carbon (C) (Zohar et al., 2017). Litaor et al. (2019) saturated WTR up to 10 mg P g^{-1} with C- and P-rich dairy wastewater and then used it as P fertiliser replacement, obtaining comparable results (and slightly higher) to a commercial fertiliser in lettuce biomass and in Olsen-P concentration in the soil. At a similar application rate, Hyde and Morris (2004) reported a lower biomass of sorghum-sudan grass after applying WTR saturated in a synthetic P solution compared to Litaor et al. (2019). According to Litaor et al. (2019), the alkalinity of the soil used allows the WTR to act as a source of P and prevents Al toxicity.

The P concentration at which the WTR is saturated may also have an impact on its performance as a P fertiliser. Raw alum sludge has been found to inhibit plant growth possibly due to P deficiency (Bugbee and Frink, 1985). Hyde and Morris (2004) examined this by using P-loaded WTR ranging from 4.9 to 60.7 mg P g^{-1} WTR. At concentrations of less than 14.6 mg P g^{-1}, WTR acted as a sink for P in the soil, whereas it acted as a source at higher P concentrations. Notwithstanding this, WTR applications – both as sink or source of P – generated a lower biomass of Sorghum-sudan in the field-scale study than that applied with mineral P fertiliser (Hyde and Morris, 2004). It has been suggested that additional inorganic P should be applied together with P-loaded alum sludge to avoid P deficiency (Dassanayake et al., 2015).

In addition to acting as a P adsorbent and a potential P fertiliser, WTR can improve soil parameters and control P losses. According to Bugbee and Frink (1985), WTR increases soil aeration and pH, and improves water holding capacity. In deciduous and coniferous acid forest soils, the pH increased between 0.5 and 1 unit one year after 17,500 kg WTR ha^{-1} were applied. In properly managed soils Al toxicity would not be expected to occur, but there is a higher risk of Al leaching when WTR is applied to acidic soils (Dassanayake et al., 2015; Ippolito et al., 2011). Additionally, raw WTR has also been effectively used to control leaching and runoff P losses from soil on its own (Agyin-Birikorang et al., 2007) and co-applied with manure or biosolids (Ippolito et al., 2009; Oladeji et al., 2006), showing no negative impacts on the plants and microbial community (Ippolito et al., 2009).

3.1.2. Iron-and steel-making slags

Slags are non-metallic coproducts from iron or steel formed by lime and impurities, such as Al, silicon, manganese (Mn), P, C and Fe (Proctor et al., 2000; Yildirim and Prezzi, 2011). The statistics for Europe in 2016 showed that 18.4 Mt of electric arc furnace slag are obtained during steel production and 24.6 Mt of blast furnace slag are obtained during iron production and, while most is recycled in construction or for metallurgical use, 14.1% of steel slag is still landfilled (Euroslag, 2019). Because of slag's high content of P-sorbing metals (Al, Fe, Ca), steel and iron slags have been investigated as P filter media, with maximum P adsorption capacities of up to 2.15 g dissolved reactive P (DRP) kg^{-1} (steel slag; Drizo et al., 2008) and 9.15 g P kg^{-1} (blast furnace slag; Asuman Korkusuz et al., 2007) being reported.

Bird and Drizo (2009), Hylander and Simán (2001), and Hylander and Simán (2006) studied the application of different types and forms of P-loaded slags to alfalfa or barley pots, and found a similar or lower plant yield compared to a mineral fertiliser (Table 2). Bird and Drizo (2009) compared the efficacy of electric arc furnace slag P-loaded with dairy wastewater (1.09 mg total P removed g^{-1} slag) and triple superphosphate (TSP) fertiliser in the growth of *Medicago sativa*. At 10 weeks and at a low application rate (approximately 3.8 mg P kg^{-1} soil) there were no significant differences compared to TSP fertiliser, but at a high rate (approximately 22.9 mg P kg^{-1} soil) electric arc furnace slag produced 76% less biomass than TSP. Hylander and Simán (2001) found that using coarser slag particles reduced the contact area with the soil and, possibly, also reduced plant availability. However, slag seemed to release P slowly to the soil and at a rate matching the plant P requirements so that P was not sorbed to soil particles. Meanwhile, Hylander et al. (2006) loaded blast furnace slag with municipal wastewater and obtained a low P concentration (around 0.3 mg P g^{-1}). After applying 0.03 g of KH_2PO_4 as mineral P fertiliser or 100 g of P-loaded blast furnace slag, both equivalent to 8.3 mg P kg^{-1} soil, they found an 11–13% lower yield produced by blast furnace slag. Even though the P-loaded slag did not perform better in agronomical trials than a mineral fertiliser, it did perform better than an unfertilised control. Therefore, some of the adsorbed P was plant-available.

The solubility of P in saturated slags depends on its composition and pH. Gustafsson et al. (2008) found that P adsorbed to blast furnace slag was solubilised as the pH was decreased to 6.9, but it was fixed again at lower pH levels. The first increase in soluble P could be attributed to Ca phosphates dissolved at near neutral pH, but at lower pH levels, P could be adsorbed again to Al and Fe oxides. At slightly alkaline conditions ($pH = 7.7$), Asuman Korkusuz et al. (2007) reported that 49% of P was loosely bounded, 43% was Ca-bounded, and only 8% was Fe-bounded in Ca-rich blast furnace slag sampled from a constructed wetland.

Slags contain different compounds, so that on the one hand, the presence of heavy metals in slags is a concern that could limit its reuse as soil amendment but on the other, the presence of micronutrients promotes its agricultural reuse. Different types of slag have been tested for determining the leaching potential of metals and it was found that metals are very tightly bound even under acidic conditions (Proctor et al., 2000). Furthermore, slags have been used as fertilisers in agriculture since the 19th century not only for their P content (Motz and Geiseler, 2001), but also because of the presence of important micronutrients like silicon (Ning et al., 2014) and Fe (Wang and Cai, 2006).

3.1.3. *Iron ochre*

Iron ochre consists mainly of Fe (III) hydroxides which precipitate from water draining from disused coal mines (Dobbie et al., 2009). In the UK, most of the precipitated ochre (4500 t dry ochre year^{-1}) is dewatered and landfilled because its formation can negatively impact water bodies (Sapsford et al., 2015). However, several studies have found that it can remove P efficiently up to >20 g P kg^{-1} (Dobbie et al., 2005). Although the reuse of the removed P has been suggested (Dobbie et al., 2009; Fenton et al., 2009), to date only Dobbie et al. (2005) have examined this in detail.

Agronomic trials with P-loaded Fe-ochre have been positive (Table 2). Dobbie et al. (2005) tested P-loaded Fe ochre on barley, birch, spruce and ryegrass in pot and field experiments. They found a slight increase in plant biomass in all experiments when using P-loaded Fe ochre applied to the soil at the same P rate (6.5 kg P ha^{-1}) as a mineral fertiliser. While only 4% of the total P was available in P-loaded ochre, in a barley pot trial there was a 175% increase in the concentration of soil available P after 4 months.

Although the risk of toxic metal mobilisation from Fe-ochre is high when it is used as a filter medium (Fenton et al., 2009), no significant increase in the concentration of most metals (Cr, Ni, Zn, Al, Cu, Pb, Fe, Mn, As, Cd) has been reported in soil compared to mineral fertilisers (Dobbie et al., 2005). Dobbie et al. (2005) found that only Fe and Mn concentrations (26 and 0.26 g kg^{-1}) were higher than no fertiliser control concentrations (12 and 0.18 g kg^{-1}) after a 4-month pot experiment. Nonetheless, the leaching of metals during adsorption and soil application should be further studied.

3.1.4. *Fly ash*

Fly ash is a residue from an incineration process and, although it can be used as construction material, in the EU up to 43% is disposed in landfills (Grace et al., 2016). Power station fly ash main components are silica (Si), Al and Fe oxides, carbon, Ca, magnesium (Mg) and sulfur. Bottom ash is coarser, has a higher permeability than fly ash, and a similar composition (Drizo et al., 1999). Oil-shale ash, which is generated when kerogenous oil-shale is burned in thermal power plants, also has a high content of Ca (Kõiv et al., 2009). Due to the presence of Al, Fe, Ca and Mg, fly ash has been used to remove P from polluted water (Drizo et al., 1999; Zhang et al., 2008) and as soil amendment to increase the P adsorption capacity of soils (Fenton et al., 2011; Seshadri et al., 2013).

Fly ash has a good P removal capacity (20.62 mg P g^{-1}) without any modification or amendments being applied (Li et al., 2006). This may be enhanced up to 25.58 mg P g^{-1} (Li et al., 2006) by thermal and acid pre-treatments. However, only a negligible amount of the adsorbed P is released as shown by Zhang et al. (2008), who found that the P sorption to fly-ash was largely irreversible. This was also found by Kõiv et al. (2012), who reported a suboptimal P content (0.61 mg P g^{-1}) in the leaves of silver birch seedlings after using P-loaded oil-shale ash (0.65 mg P g^{-1}) as a substrate medium.

Although fly ash has been reported to improve the physico-chemical characteristics of the soil (texture, bulk density, water holding capacity), which are related to an increase in plant yield (Ram and Masto, 2014), it has a low permeability (Zhang et al., 2008) and the potential risk for metal leaching is high (Grace et al., 2016). Furthermore, fly ash with less than 10% CaO (class F fly ash; Standard ASTM C618; ASTM International, 2019) mixed with lime or fly ash with more than 20% CaO (class C fly ash; Standard ASTM C618; ASTM International, 2019) have self-cementing properties (Malik and Thapliyal, 2009), which should be avoided in agricultural soils. A general recommendation for fly ash application to the soil is not possible due to the diversity in fly ash and soils characteristics, as well as agro-climatic conditions (Ram and Masto, 2014). Therefore, further investigation is needed to understand the characteristics of fly ash blending with other waste products, as well as more detailed field and laboratory studies, monitoring of contaminants and other topics (Ram and Masto, 2014).

3.1.5. *Mixed materials*

Some industrial waste materials with no natural P adsorption capacity have been processed to be used as filter medium for P removal and, subsequently, as a fertiliser replacement. For example, Li et al. (2018) pyrolysed sawdust with dolomite to synthesise a hybrid carbon composite with CaO and MgO for improved P removal (Table 2). This engineered material was saturated with swine slaughterhouse wastewater, where a combination of precipitation and electrostatic attraction mechanisms removed $H_2PO_4^-$ and HPO_4^{2-} anions and formed Mg—P and Ca—P minerals on the surface. A P content of up to 22.4 mg P g^{-1} was obtained and the material was applied at rates >220 mg P kg^{-1} soil. Although a slow and pH-dependent release (higher at pH 5) of P was identified, the carbon composite produced a yield of Chinese brassica of 200% higher than a no mineral fertiliser control.

A hybrid biomaterial was synthesised by Wang et al. (2015), who immobilised Mg in Artemia egg shells and saturated it to 0.07 mg P g^{-1} (Mehlich III-P). Artemia is a food source in aquaculture and the egg shells is a waste mainly composed of chitosan. The saturated Artemia biomaterial was applied to the soil where the early-stage seedling growth of mung bean was tested. Phosphorus-saturated Artemia shell increased plant height by 59% compared to a no fertiliser control, suggesting some of the adsorbed P was plant available. The release of P from P-saturated Artemia shell applied to soil was also compared to the release of P from KH_2PO_4 and Wang et al. (2015) found that, while KH_2PO_4 released P to the soil quickly and was completely exhausted in <20 days, P-saturated Artemia shell released a sustained amount of 0.005 mg P g^{-1} to 0.01 mg P g^{-1} for at least 30 days. However, none of these hybrid materials were tested against a mineral P control and the trials were conducted for a short time (2—3 weeks), so any potential negative effects were not assessed.

3.1.6. *Other materials with high P adsorption capacity*

Many other industrial waste materials, such as bauxite and mollusc shells, have been identified as potential P filter media but their use as P fertilisers in agriculture has not yet been fully studied. Bauxite or red mud residue is generated from the Al industry and is currently disposed in specialised facilities (Grace et al., 2016). It contains mainly Al, Fe, titanium, Ca and silicon oxides (Cusack et al., 2019), and can be activated with a thermal treatment or acid treatment to improve its capacity to mitigate contaminants (Liu et al., 2011). Brennan et al. (2019) found that partially P-saturated bauxite acts as a sink of P in the soil and can create P deficiency. Furthermore, at neutral or alkaline pH values, metal leaching from bauxite may occur (Brennan et al., 2019; Cusack et al., 2019).

Egg shells and mollusc shells are a waste material from the food industry with a high concentration of Ca (King'ori, 2011) and high porosity (Abdel-Khalek et al., 2017). Several studies have tried to identify potential reuse options. For example, eggshells have been used as adsorbents of cationic and anionic dyes (Abdel-Khalek et al., 2017). Calcined eggshells have high P adsorption capacity (23.02 mg PO_4^{3-} g^{-1}) (Köse and Kivanç, 2011), but they have not yet been tested as a fertiliser after P saturation. In addition, they can potentially be used as a liming material in the soil. Crab shell powder with a $CaCO_3$ concentration of 27% was used as a liming material in acid soils (4.6–4.8 pH), increasing the pH to about 6.4–7.1 after applying 15,000 kg ha^{-1} (Adiloglu and Adiloglu, 2009). Eggshells contain more $CaCO_3$ (98%) than limestone and they have also been used as an effective liming material (King'ori, 2011).

3.2. Agricultural waste

3.2.1. Biochar

Biomass used as an energy source through pyrolysis produces biochar as a by-product. Biochar has potential for contaminant sorption, but its properties are variable and depend on the feedstock used and processing conditions (Chintala et al., 2013). Although most biochars have a low P adsorption capacity (Yao et al., 2012), anaerobically digested sugar beet tailings biochar were found to have a maximum adsorption capacity of 43.40 mg P g^{-1} due to the presence of MgO particles on the surface of the biochar (Yao et al., 2011). Additionally, modified biochars (magnetic biochar, MgO- or AlOOH-biochar nanocomposites) have a good P removal capacity (up to 272.30 mg P g^{-1}; Mohan et al., 2014).

Chen et al. (2018) synthesised MgO cow dung biochar and Li et al. (2016) produced MgO magnetic sugarcane biochar for P adsorption and as a P fertiliser (Table 3). The main removal mechanism of the Mg-enriched biochars was precipitation of $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-} anions with Mg on the surface and inner pores, but also a combination of complexation and electrostatic attraction processes were identified. Both experiments increased the yield of the crop (lettuce 42% and ryegrass 206%, respectively) compared to a no fertiliser control, but none included a mineral fertiliser control. Additionally, after application of cow dung biochar there was a significant increase in available P in the soil. Yao et al. (2013) tested the germination and early stage seedling growth of grass with and without P-laden biochar prepared by pyrolysing Mg-enriched tomato leaves. The seed germination rate increased from 53% (without biochar) to 85% (with biochar) and the shoot length increased by 72%. Although the results are positive compared to a no fertiliser control, to better assess the use of P-loaded biochars as fertilisers, their effectiveness should also be compared to a mineral P fertiliser.

In addition to the potential supply of P, the application of biochar to soil has also shown C sequestration capacity, increased microbial activity, increased organic matter, water retention, and a decrease in nutrient leaching and erosion (Mohan et al., 2014). Further economic and environmental studies are needed to justify the production of modified biochars for P removal and recycling to soil, as well as field studies comparing it to a mineral fertiliser for plant growth.

3.2.2. Other materials with a potential as a P fertiliser

Diverse agricultural waste materials in their raw form or after processing have been identified as potential P adsorbents. Coconut shells have been successful in removing P after different treatments such as limestone addition (3 g P kg^{-1}), NaOH modification (200 g P kg^{-1}), $ZnCl_2$ activation (5.1 g P kg^{-1}) or production of activated carbon (Grace et al., 2016), but their FRV has not been tested. Rice husk, which is generated in large quantities (700 million tonnes in Asia annually), is currently used for power production and as raw material for several products. However, its alternative use in wastewater treatment has been investigated for the removal of P as a raw material or after chemical activation (Grace et al., 2016). More research regarding the adsorption capacity of these materials and reutilisation as fertiliser is needed.

3.3. Construction and demolition waste

3.3.1. Crushed glass

Crushed glass is produced either during C&D waste generation or when waste glass containers are collected. High-purity glass can be remanufactured into new glass containers and, in the EU, up to 73% of glass packaging was recycled in 2015 (Mohajerani et al., 2017). Although there has been extensive research to reuse crushed waste glass in construction applications and prevent landfill disposal, it is still not widely used for this purpose (Mohajerani et al., 2017). Additionally, this material has been tested as a filter medium to remove turbidity, particles and metals (Rutledge and Gagnon, 2002). However, its performance with P removal is rather low with an adsorption capacity of only 0.01 mg P g^{-1} (Healy et al., 2010).

In order to increase the P sorption capacity of crushed glass, it has been mixed with Ca-rich materials (such as oyster shells) and burned at 900 °C to produce a porous glass material (PGM) that has a higher adsorption capacity due to its Ca content (Nakazawa et al., 2006). Nakazawa et al. (2006) found that after the material was saturated to a concentration of 0.65 mg P g^{-1}, the glass and crushed oyster shells mixture and a mineral fertiliser were applied separately to tomato plant pots at a rate of 129 mg P kg^{-1} soil. In comparison to the mineral fertiliser, the PGM mixture produced a shoot dry biomass 90% lower than that produced by the mineral fertiliser (Table 3). An additional mineral P application to the P-loaded PGM increased the biomass compared to P-loaded PGM only, which could indicate that the P-loaded PGM caused P deficiency in the soil.

An advantage of the high $CaCO_3$ content is that when it is used on acid soils it can increase the pH of the soil and as a result, the solubility of phosphate. Nakazawa et al. (2006) found a 10.8% increase in soil pH and 9.8% increase in soil available P compared to a mineral fertiliser. The authors conclude that a lower application rate of PGM which is mixed with a higher proportion of Ca-rich material may be more beneficial to the soil and may increase the P adsorption capacity, but this has not been tested yet. Further analyses are needed to evaluate the presence of impurities on the glass material, for example, heavy metals that could be transferred to the soil.

3.3.2. Crushed concrete

Crushed concrete, demolished concrete, or recycled concrete aggregate contain P-binding metals (Mg, Ca, Fe, Al), and has been used as a P adsorbent in the laboratory (Callery and Healy, 2019; Deng and Wheatley, 2018) and at full-scale (Sønderup et al., 2015). Pre-treatment by heating up to 900 °C has been used to increase its sorption capacity by turning Ca carbonate to quicklime (Kang et al., 2017). The adsorption capacity of crushed concrete is very high, between 17.3 mg g^{-1} to 70.9 mg g^{-1} (Grace et al., 2016), and, after P saturation, a high proportion (43%) is labile (Deng and Wheatley, 2018), which means that it could potentially be used as a P fertiliser replacement and provide plant-available P to the soil. However, at the time of writing, this has not been examined.

The composition of the P-loaded crushed concrete would have to be analysed before application to the soil because of the risk of heavy metal contamination. Concrete buildings accumulate heavy metals over time and concrete used as a filter medium in wastewater treatment also retains heavy metals (Sønderup et al., 2015). Therefore, reused concrete could contain a high concentration of heavy metal. Another characteristic to examine is the pH. Sønderup et al. (2014) measured an elevated pH in the effluent of a concrete filter for water and wastewater treatment, particularly in the initial stages of operation. An increase in the soil pH would also be expected when mixing spent concrete with the soil. This liming potential could be considered an advantage in acid soils, but a disadvantage on already alkaline soils.

3.4. Natural materials

3.4.1. Limestone

Limestone is a carbonate sedimentary rock that consists mainly of $CaCO_3$ and is extracted from quarries and used for agriculture, construction or decorative purposes, among other applications. Some is fragmented during extraction and when it is not reused for construction, it is deposited in landfills (Mateus et al., 2012). Limestone is a common material that, when it has the right characteristics, can effectively remove P due to its large concentration of Ca. It has been successfully used to remove up to 92% P in wetlands (Ballantine and Tanner, 2010) and it has an adsorption capacity ranging from 0.398 g P kg^{-1} (Mateus et al., 2012) to 2 g P kg^{-1} (Guan et al., 2009).

After saturation, limestone has been applied to the soil as a P fertiliser replacement. Limestone and burned lime were loaded with synthetic P solution by Hylander and Simán (2001) to a concentration of 0.78 mg P g^{-1} and 2.29 mg P g^{-1}, respectively (Table 4). Although both materials resulted in a yield reduction of barley compared to a mineral fertiliser, burned lime performed better, and at the high application rate of limestone the growth was completely impeded. The low yields could have been caused by Mn deficiency related to the liming effect of the materials tested which was also accompanied by symptoms of grey speck disease. Hylander et al. (2006) used limestone to remove P from wastewater (final concentration of 0.4 mg P g^{-1} limestone) and then mixed it with soil to evaluate barley growth, which was inhibited by 19% compared to an untreated soil.

Both experiments by Hylander and Simán (2001) and Hylander et al. (2006) produced an increase in soil pH (Table 4). Hylander and Simán (2001) reported a pH increase in lime- and limestone-applied soil from 6.3 to 8.7, although the application of the same amount of raw lime (without loaded P) had a higher liming potential and increased the soil pH up to 12. It is likely that the alkaline characteristics of the material, even after P saturation, hindered the growth of plants, so its use should be restricted to highly acidic soils (Hylander et al., 2006). Additionally, the accumulation of metals in limestone filters should be assessed before application to soil, since a high removal of Zn, Cu, Mn, Ni and Cr was found with limestone and other materials (Renman et al., 2009).

A specific type of limestone, dolomite, has also been tested as a P adsorbent and potential P fertiliser. Dolomite is a carbonate mineral composed of Ca and Mg carbonate ($CaMg(CO_3)_2$). Dolomite has been used efficiently as a P adsorbent on its own (Piol et al., 2019) and as a dolomite-alginate composite (Huang et al., 2019). Piol et al. (2019a) extracted the adsorbed P from dolomite using NH_4Cl and also confirmed that P solubilising bacteria can solubilise P from exhausted dolomite samples which had undergone a desorption process, although this increased solubility of P did not impact *Lactuca sativa* root growth. Huang et al. (2019) found a maximum P adsorption capacity of 28 mg g^{-1} and showed that the dolomite-alginate beads could work as a slow release fertiliser, as they released 40% of the phosphate in the first 10 days and up to 90% in 60 days. However, this was tested in a desorption study with water, not in the soil.

3.4.2. Opoka

Opoka is a $CaCO_3$- and SiO_2-rich sedimentary rock found in South-East Europe and Russia, which has been used for water treatment especially in its calcinated form (Brogowski and Renman, 2004). After P removal, natural opoka has also been used for P recycling to soil in pot experiments with barley, but with adverse impacts on plant growth and plant P content (Hylander et al., 2006; Hylander and Simán, 2001) (Table 4). The application of P-loaded opoka to the soil increased the pH of the soil up to 25% and increased soil available P significantly, suggesting that it has potential to act as a source of P in acid soils. However, Hylander and Simán (2001) found that Mn deficiency may have caused a lower plant yield. Further studies are required to assess the potential use of P-loaded opoka for P fertilisation.

3.4.3. Sand

Sand is commonly used as a filter material which, on its own, has limited P removal capacity below 0.3 mg P g^{-1} (Ca-rich sand; Del Bubba et al., 2003), but it can be increased by Fe oxides or Al hydroxides coating or naturally-occurring Fe-rich sand deposits (Ballantine and Tanner, 2010). The P adsorption capacity may be increased up to 1.43 mg P g^{-1} with Fe oxide coating (James et al., 1992). However, the reuse of P-rich sand as a fertiliser may be limited due to its low concentration of P compared to other materials.

Kvarnström et al. (2004) compared the performance of different types of sands used in domestic wastewater infiltration basins and a wetland, and an Fe-rich fine sand with a P content between 0.37 and 0.56 mg P g^{-1}, and compared their FRV with a mineral P fertiliser in ryegrass pots. Although 15 and 29% of the P was plant-available and Fe-rich sand had the lowest proportion of available P because it removed mostly organic P, there were no significant differences in plant yield compared to a mineral P fertiliser (Table 4). Hylander et al. (2006) found a similar total P concentration (0.46 mg g^{-1}) in quartz sand used as an inert reference filter material to treat municipal wastewater, and although the yield was 20% higher than a no fertiliser control, it was 35% lower than a mineral fertiliser. Although the amount of available P in the sand was not analysed by Hylander et al. (2006), the sand did not remove any soluble P during the treatment since it acted as a physical filter only so it would not be expected to provide much plant-available P to the soil.

Although the results of the studies published to date do not look very promising, the reuse of P-rich sands for soil application could improve the soil structure, reducing compaction and increasing the porosity for turf establishment (McCoy, 1998) and it could be an effective amendment in the amelioration of saline-sodic soils (Liu et al., 2010).

3.4.4. Soil

Soils have different P retention capacities depending on their physicochemical characteristics and composition. Allophanic soils (rich in Fe and Al hydrous oxides) in New Zealand have been effectively used as P adsorbent from wastewater and recycled to agricultural soil to provide P with a FRV equivalent to 61% of inorganic P fertiliser (Cheuyglintase et al., 2018). Aluminium- and Fe-rich soils, such as a spodic B horizon, have a high adsorption capacity of up to 1.57 mg P g^{-1} (Hylander and Simán, 2001). Despite this, the reuse of P-loaded spodic B horizon soil as a fertiliser replacement has produced negative results. Hylander and Simán (2001) found that the biomass and P content of barley, as well as soil available P, were lower after the application of P-loaded spodic soil compared to a mineral fertiliser, while other materials tested increased available P in the soil (Table 4). The spodic soil had a high concentration of Al and Fe compared to the concentration of Ca predominant in the other materials tested (e.g. opoka, limestone). In acid to neutral soils such as the one in the study, P would normally be less available when bound to Al and Fe compared to Ca. Therefore, the selection of soil as P filter material and P fertiliser afterwards will depend on its chemical composition and pH of the soil where it will be applied.

3.4.5. Modified zeolites

Zeolites are natural or synthesised aluminosilicate minerals that are structured as three-dimensional frameworks with inner pores and channels and a high cation exchange capacity (Bansiwal et al., 2006; Ganrot, 2012). Zeolite can be used to remove contaminants in wastewater and it has shown a maximum P adsorption capacity of 2.15 mg P g^{-1} (Sakadevan and Bavor, 1998) as unmodified zeolite and in a surfactant-modified zeolite, the adsorption increased by 4.9 times (Bansiwal et al., 2006).

Surfactant-modified zeolite was studied as a carrier of P and slow release P fertiliser in a percolation test (Bansiwal et al., 2006). Raw natural zeolite (clinoptilolite) was treated with $Ca(OH)_2$ and used to remove P from urine (Mitrogiannis et al., 2018). Phosphorus in the $Ca(OH)_2$-zeolite was later desorbed, where up to 84.9% of P could be recovered. It was found that $Ca(OH)_2$-zeolite recovered NH_4 as well (Mitrogiannis et al., 2018). In addition to the fertiliser potential, zeolite can also work as a soil conditioner and its composition is similar to the soil, so it is not expected to alter its characteristics (Bansiwal et al., 2006). However, the direct application of P-loaded zeolites to the soil in a plant system has not yet been studied.

3.5. Synthetic materials

3.5.1. Filtra P

Filtra P is a commercial product used for P removal in wastewater treatment systems manufactured by burning lime and gypsum with Fe. After a saturation with synthetic P to 0.71 g P kg^{-1}, Cucarella et al. (2007) tested Filtra P in two pot experiments, one with barley grown on pH neutral soil and another with ryegrass in acidic soil (Cucarella et al., 2008). Both experiments reported an increase in plant P content, but the yield of barley in the neutral soil was slightly lower and the yield of ryegrass in the acidic soil was slightly higher than a mineral fertiliser applied soil (Table 5). The alkaline pH of the material (11.5) was advantageous in an acidic soil because it acted as a liming agent and its addition improved the cation exchange capacity of the soil. However, Cucarella et al. (2008) also found a higher concentration of lead (7 mg kg^{-1}) compared to other studied media and traces of mercury (0.02 mg kg^{-1}), which could impede its extended use in agriculture.

3.5.2. Polonite

Polonite® is another commercial material used as filter medium to remove P from wastewater treatment systems. It is obtained by the calcination of opoka, which transforms Ca carbonate into Ca oxide, increasing the P adsorption capacity of the material. Similar to opoka, Polonite is rich in Ca and Si and due to its elevated pH and high concentration of Ca, P is efficiently removed by precipitation (Cucarella et al., 2009).

Cucarella et al. (2009) used domestic wastewater P-saturated Polonite in a field trial with established grass cover in a mountain meadow in acidic soil (pH 5.2). In this experiment, the biomass, plant P concentration, soil available P and soil pH were increased, confirming the potential use of P-loaded Polonite as a fertiliser in acidic soils after reaching the end of its lifetime as a filter medium. Additionally, compared to Filtra P, the heavy metal content was lower and the P content was higher (Cucarella et al., 2008).

However, Hylander and Simán (2001) and Hylander et al. (2006) found negative results when using burned opoka and Polonite compared to a mineral fertiliser also on acidic soils (pH 5.3–5.7). The yield in the first experiment was even lower than no P control, which was attributed to early Mn deficiency and grey speck disease symptoms due to the liming effect of Ca-rich materials; in the second, the yield was higher than no P fertiliser, but was not as good as with mineral fertiliser.

3.5.3. Wollastonite

Wollastonite is an abundant Ca metasilicate compound with a high concentration of CaO (50%), that has shown promising P removal efficiency of more than 80% removal of soluble reactive P in wetland systems (Brooks et al., 2000). The use of wollastonite as a P filter medium and, subsequently, as a P fertiliser had similar results to Filtra P and Polonite as reported by Cucarella et al. (2007) and Cucarella et al. (2008), with the difference that the total P in the loaded medium was only 0.25 mg P g^{-1} and the biomass in both experiments was unaffected by the application of wollastonite to barley and ryegrass pots. Wollastonite had a high content of Mn after saturation (around 400 mg kg^{-1}), another important plant nutrient, and a low concentration of heavy metals, compared to other material tested. It is also naturally rich in Si, which can improve soil structure and is also a plant nutrient (Cucarella et al., 2008). Nevertheless, its P adsorption capacity is low to be considered a reliable P filter medium and P fertiliser (Cucarella et al., 2008).

3.5.4. Expanded clay aggregates

LECA® LWA (light weight aggregate) and Filtralite P® are commercial products commonly used for water filtration among other applications that contain limestone for improved P removal (Filtralite, 2019). Light-weight expanded clay aggregates are highly porous clay structures. After reaching the end of their lifetime, the filter media need to be replaced and the P taken up, which is bound to Al and Fe oxides and hydroxides (Hylander and Simán, 2001), could potentially be recycled into the soil.

Phosphorus-loaded LECA and Filtralite P have been used as a fertiliser replacement with poor results where none of the studies have found a higher plant yield and/or plant P content than that of mineral P fertiliser. A reduction in plant biomass or plant P content was observed by Hylander and Simán (2001), who used laboratory P-loaded LECA (0.5 mg P g^{-1}) and by Jenssen et al. (2010), who sampled Filtralite P (1.70 mg P g^{-1}) from a filter bed that had been in operation for 1–2 years and also used a laboratory saturated sample (9.03 mg P g^{-1}). Kvarnström et al. (2004) collected P-loaded LECA (0.36 mg P g^{-1}) from a wetland that had been in operation for 6 years and did not observe a difference in plant yield against mineral fertiliser or no fertiliser control. There was only an increase in plant P content which was mainly derived from the soil and only a low concentration was derived from the P-loaded material addition according to the isotopic composition of P in the plant.

Since the expanded clay aggregates contain limestone to increase P adsorption capacity, they can act as liming agent when applied to acidic soils. Where an increased P uptake was observed, it could be due to the liming effect of the materials instead of the P application. There was a low heavy metal sorption by the LWA in a wetland system and previous trials had reported a low heavy metal sorption capacity, so the risk of heavy metal contamination into the soil is low (Kvarnström et al., 2004). Conversely, organic carbon and nitrogen (NO_3^-, NH_4^+) were accumulated in the LWA material, which are also valuable plant nutrients.

The total P taken up by the filter medium was lower in real conditions than in the laboratory, so a high application rate would be needed to supply P to the soil as a single source of P. Kvarnström et al. (2004) suggested replacing only 15% of the commercial P fertiliser with P-loaded filter medium instead of using the P-loaded medium as the only source of P.

3.5.5. *Layered double hydroxides*

Everaert et al. (2016), Kong et al. (2019) and Qiao et al. (2019) synthesised layered double hydroxides (LDH) for the removal of P and reuse as fertiliser. LDH can be very efficient materials for P removal, since they are engineered for P removal and low-cost raw materials can be used for their fabrication (natural clays and minerals). LDH remove orthophosphates (in the form of $H_2PO_4^-$ and HPO_4^{2-}) mainly by chemisorption through ion exchange, but hydroxyl phosphate precipitation and inner-pore diffusion have also been identified (Everaert et al., 2016; Kong et al., 2019; Qiao et al., 2019). However, the synthesis of the LDH materials involves the use of strong acids and alkalis (HNO_3, NaOH, NH_4OH) and energy intensive operations such as heating, stirring, centrifuging, autoclaving, drying, ultrasonic dispersion and freeze-drying.

Kong et al. (2019) synthesised a layered double hydroxide based on palygorskite (attapulgite), a low cost hydrated Mg–Al silicate clay, and periclase, a Mg oxide mineral, and obtained a very high maximum adsorption capacity of 225.91 mg P g^{-1}. For the fertiliser experiment, they used a LDH material loaded with 0–88 mg P g^{-1} and obtained good results. At the lowest dose there was no difference in yield against struvite, a slow-release fertiliser, or KH_2PO_4, but at higher doses it increased the content of P in the plants and yield against KH_2PO_4 and struvite. Everaert et al. (2016) also found increased plant biomass compared to a mineral fertiliser with increasing applications of P using Mg–Al LDH with 40 mg P g^{-1} but only when it was used in an acid soil. Qiao et al. (2019) found a 10% increase in plant biomass and 13% in height against triple superphosphate and a soil pH increase from 5.7 to 6.5 when using magnetic Fe_3O_4/Zn–Al–Fe–La-LDH with 260 mg P g^{-1}.

From a sequential extraction test, it was found that the amount of extractable P from the LDH material was higher than struvite and that acidification, microbial hydrolysis and carbonate around the respiring roots are the main mechanisms of P release (Kong et al., 2019). This means that the release of P is not only slow, but spatiotemporally controlled near to the plant roots and in response to the plant strategies to overcome P deficiency (Everaert et al., 2016). LDH materials may also contain Mg (Kong et al., 2019), which could be an additional plant nutrient, Al (Everaert et al., 2016) which is only harmful in soils with pH > 5, and Zn, Al, Fe and La (Qiao et al., 2019) from which only Al was present in a higher concentration in the leaves of LDH amended plants (0.06 mg g^{-1}) than in the control treatment.

3.5.6. *Other engineered materials*

Karunarathna et al. (2019) developed a novel material that allows a light-controlled release of P using biodegradable Fe (III)–polysaccharide gels. After saturation with synthetic P solution, where P was removed Fe (III)–P binding, a total P concentration of 1.49 mg PO_4 g^{-1} was obtained (J. Karunarathna, *personal communication*) and its application to kale pots at 30 mg PO_4 kg^{-1} soil resulted in a 30% increase in aboveground biomass against no fertiliser control. Further experiments are needed to confirm the potential use of this material as a P fertiliser in the soil comparing its efficiency against a mineral P fertiliser.

4. Factors that may affect performance of saturated filter media as fertiliser replacement

The most important factors affecting the performance of saturated filter media, as well as the consequences (positive or negative) following their land application, and measures to overcome any negative impacts are listed in Table 6. These factors have been grouped into four classifications: adsorption capacity of the media, chemical composition of the media, soil pH, and composition of water used for saturation.

The P concentration that a saturated medium can achieve and the amount of P it will desorb depend not only on its inherent maximum adsorption capacity, but also on the influent concentration to the adsorption system with which it is saturated and the type of adsorption mechanism that occurs. Adsorption occurs through physical sorption (physisorption), chemical sorption (chemisorption), or a combination of both. While physisorption is a weak type of adsorption because it mainly depends on Van der Waals bonding, chemisorption is mainly an irreversible reaction (Grassi et al., 2012). It has been found that at lower inlet concentrations the main adsorption mechanism is physisorption and at higher concentrations, chemisorption occurs through complexation, ligand exchange and precipitation of P with metals (Hua et al., 2016). However, the type of adsorption is also defined by the filter medium physical and chemical characteristics such as chemical composition, presence of functional groups, point of zero net proton charge (pHPZNPC), crystallinity and porosity. Additionally, the solution pH plays a major role in the adsorption process and adsorption capacity. Therefore, P desorption from a saturated filter medium will be defined by a complex combination of all these factors and it is difficult to predict.

Filter media with low P adsorption capacity can remove solids from water but very little dissolved P, which causes a low available P content in the medium (Hylander et al., 2006). Conversely, media with high P adsorption capacity can have a good yield/amendment ratio provided other factors are considered, but a high adsorption capacity can also have a negative impact when the medium acts as a sink of P in the soil, causing P deficiency (Brennan et al., 2019; Hyde and Morris, 2004). Among the proposed solutions for these problems, the incorporation of P-sorbing metals to the materials has been suggested to increase the P adsorption capacity (James et al., 1992) and when there is a risk for the medium to act as a sink of P, additional mineral P can be applied together with the saturated filter medium (Hyde and Morris, 2004).

The next group of factors is the chemical composition of the media. A high content of heavy metals, naturally present in the soil or acquired during the saturation, can have a negative impact if the medium is applied to crops that can enter the human food chain (Cheuyglintase et al., 2018; Paruch et al., 2007). In these cases, the application rate can be reduced to safe levels based on the metal content of the soil, or, alternatively, the media may be applied to forests instead of agricultural soils. In some cases, the saturated filter media may also contain beneficial elements such as plant micronutrients that improve plant status and improve soil structure (Cucarella et al., 2008).

The next factors relate to the amount of P-sorbing metals. The application of Ca-rich media has been mostly advantageous to acidic soils that benefit from the liming capacity of the media (Adiloglu and Adiloglu, 2009; Cucarella et al., 2008; Hylander et al., 2006), while Al-rich media can cause Al toxicity and P fixation on acidic soils but benefit from lower Al—P fixation on alkaline soils (Codling et al., 2007; Hylander and Simán, 2001; Litaor et al., 2019). Conversely, the high content of P-sorbing metals induces a slow but sustained release of P that prevents P losses (Huang et al., 2019; Wang et al., 2015). Some solutions that have been tried to solve the low P availability from P sorbing media are the use of P solubilising microorganisms (Gaind and Gaur, 2002; Lukashe et al., 2019; Marhual et al., 2011; Piol et al., 2019) or previously mixing the media with manure (Urvashi et al., 2007). Both solutions have been shown to increase the amount of plant available P.

Finally, the composition of water used for saturation can also determine the success or failure of the reuse of P-saturated filter media. If the saturating solution has a high concentration, the system will have a higher driving force for overcoming the mass transfer resistance, as described by Baral et al. (2009), and the uptake capacity of the medium will increase. Naghizadeh et al. (2013), Gupta and Babu (2009) and Saadi et al. (2013) observed an increased adsorption capacity of filter media in column experiments when the influent concentration of different contaminants was increased. Additionally, a P-poor water source has low economic potential for P recycling (Rittmann et al., 2011). Another factor in the composition of the water is the concentration of organic matter which can both increase or decrease the release of P to the soil. A water solution with low organic matter content will cause a higher removal capacity but lower desorption due to more tightly bound P compared to media saturated in organic matter-rich solution (Renman et al., 2009; Zohar et al, 2017, 2018). A final issue is the transfer of pathogenic microorganisms and heavy metals from filter media to the soil (Jenssen et al., 2010). Although this has not been reported, it should also be further investigated and the media treated accordingly, especially when they remove P from wastewater.

5. Conclusion

The use of filter media to adsorb P from nutrient-rich water streams is a simple and low cost method to recover P which can be safely reused as a bio-based fertiliser when the correct combination of water, soil and filter medium characteristics are carefully selected. Industrial waste materials produce varied results depending on the experiment conditions and type of material; C&D waste has not been evaluated extensively as a P source yet; natural materials tend to have lower adsorption capacities and provide neutral to negative results against a mineral fertiliser; and agricultural waste as biochar and synthetic materials are promising but more information is needed on longer term trials and mineral fertiliser comparison experiments. These results showed that the FRV of a material is affected by several confounding factors, meaning that an overall conclusion regarding the potential of P-saturated waste media as a fertiliser is difficult to make. However, some insights may be attained if the water-soil-filter medium system is considered in its entirety.

To achieve a successful waste management strategy where P-saturated filter media are reused as P fertilisers, the adsorption capacity and chemical composition of the medium, soil pH, and composition of water used for saturation need to be assessed in combination. It has been found that the filter media remove P mainly as orthophosphates through a combination of physisorption and chemisorption such as inner pore diffusion, electrostatic attraction, anion exchange, complexation, ligand exchange and precipitation. The dominant adsorption mechanism will limit the rate of P desorption and its subsequent plant availability. A low adsorption capacity causes a lower yield to amendment ratio, which could be detrimental for plant growth when the material contains other components that are not considered plant nutrients. Meanwhile, a high adsorption capacity can cause the filter medium to act as a sink of P in the soil if it is not completely saturated. The chemical composition of the medium determines its P adsorption mechanism and the strength of the P bond which, in turn, affects its plant availability. The combination of acidic soil with an alkaline medium provides a liming effect and increased P availability, but these alkaline media should not be used in basic soils to prevent decreased availability of other nutrients. Lastly, organic matter-rich water is advantageous when combined with media that form strong P bonds which would be otherwise not available for plant uptake, and care should be taken when heavy metals or pathogens are present in the water since these could be transferred to the soil and plants.

Only few studies compare the performance of the media under different conditions and more information would be valuable in this regard. Further study is also necessary to explore methods to overcome low FRV that would support the circular economy of P-saturated filter media using P solubilising microorganisms, mixing with other soil amendments (e.g. manure) for releasing more adsorbed P, and testing different soil types and competing ions in the water and plants according to the media chosen.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Abdel-Khalek, M.A., Abdel Rahman, M.K., Francis, A.A., 2017. Exploring the adsorption behavior of cationic and anionic dyes on industrial waste shells of egg. J. Environ. Chem. Eng. 5, 319—327. https://doi.org/10.1016/j.jece.2016.11.043.

Adiloglu, A., Adiloglu, S., 2009. Lime effectiveness of Crab shell powder in acid spodosols. Asian J. Chem. 21, 3179—3185.

Agyin-Birikorang, S., O'Connor, G., Jacobs, L., Makris, K., Brinton, S., 2007. Long-term phosphorus immobilization by a drinking water treatment residual. J. Environ. Qual. 36, 316—323. https://doi.org/10.2134/jeq2006.0162.

Agyin-Birikorang, S., O'Connor, G.A., 2007. Lability of drinking water treatment residuals (WTR) immobilized phosphorus. J. Environ. Qual. 36, 1076—1085. https://doi.org/10.2134/jeq2006.0535.

ASTM International, 2019. ASTM C618 - 19, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. West Conshohocken, PA.

Asuman Korkusuz, E., Beklioğlu, M., Demirer, G.N., 2007. Use of blast furnace granulated slag as a substrate in vertical flow reed beds: field application. Bioresour. Technol. 98, 2089—2101. https://doi.org/10.1016/j.biortech.2006.08.027.

Babatunde, A.O., Zhao, Y.Q., Burke, A.M., Morris, M.A., Hanrahan, J.P., 2009. Characterization of aluminium-based water treatment residual for potential phosphorus removal in engineered wetlands. Environ. Pollut. 157, 2830—2836. https://doi.org/10.1016/j.envpol.2009.04.016.

Bacelo, H., Pintor, A.M.A., Santos, S.C.R., Boaventura, R.A.R., Botelho, C.M.S., 2020. Performance and prospects of different adsorbents for phosphorus uptake and recovery from water. Chem. Eng. J. https://doi.org/10.1016/j.cej.2019.122566.

Bai, L., Wang, C., He, L., Pei, Y., 2014. Influence of the inherent properties of drinking water treatment residuals on their phosphorus adsorption capacities. J. Environ. Sci. (China) 26, 2397—2405. https://doi.org/10.1016/j.jes.2014.04.002.

Ballantine, D.J., Tanner, C.C., 2010. Substrate and filter materials to enhance phosphorus removal in constructed wetlands treating diffuse farm runoff : a review. https://doi.org/10.1080/00288231003685843, 53, 71-95.

Bansiwal, A.K., Rayalu, S.S., Labhasetwar, N.K., Juwarkar, A.A., Devotta, S., 2006. Surfactant-modified zeolite as a slow release fertilizer for phosphorus. J. Agric. Food Chem. 54, 4773—4779. https://doi.org/10.1021/jf060034b.

Baral, S.S., Das, N., Ramulu, T.S., Sahoo, S.K., Das, S.N., Chaudhury, G.R., 2009. Removal of Cr(VI) by thermally activated weed Salvinia cucullata in a fixed-bed column. J. Hazard Mater. 161, 1427—1435. https://doi.org/10.1016/

j.jhazmat.2008.04.127.

Barca, C., Gérente, C., Meyer, D., Chazarenc, F., Andrès, Y., 2012. Phosphate removal from synthetic and real wastewater using steel slags produced in Europe. Water Res. 46, 2376–2384. https://doi.org/10.1016/j.watres.2012.02.012.

Batjes, N.H., 1997. A world dataset of derived soil properties by FAO-UNESCO soil unit for global modelling. Soil Use Manag. 13, 9–16. https://doi.org/10.1111/j.1475-2743.1997.tb00550.x.

Bird, S.C., Drizo, A., 2009. Investigations on phosphorus recovery and reuse as soil amendment from electric arc furnace slag filters. J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 44, 1476–1483. https://doi.org/10.1080/10934520903217922.

Brennan, R.B., Murnane, J.G., Sharpley, A.N., Herron, S., Brye, K.R., Simmons, T., 2019. Soil phosphorus dynamics following land application of unsaturated and partially saturated red mud and water treatment residuals. J. Environ. Manag. 248, 109296. https://doi.org/10.1016/j.jenvman.2019.109296.

Brogowski, Z., Renman, G., 2004. Characterization of Opoka as a basis for its use in wastewater treatment. Pol. J. Environ. Stud. 13, 15–20.

Brooks, A.S., Rozenwald, M.N., Geohring, L.D., Lion, L.W., Steenhuis, T.S., 2000. Phosphorus removal by wollastonite: a constructed wetland substrate. Ecol. Eng. 15, 121–132. https://doi.org/10.1016/S0925-8574(99)00056-7.

Bugbee, G.J., Frink, C.R., 1985. Alum sludge as a soil amendment: effects on soil properties and plant growth. Conn. Agric. Exp. Stn. Bull. (New Haven) 8, 1–7. https://doi.org/10.5962/bhl.title.51101.

Callery, O., Healy, M.G., 2019. A novel method to rapidly assess the suitability of water treatment residual and crushed concrete for the mitigation of point and nonpoint source nutrient pollution. Resour. Conserv. Recycl. X 2, 100010. https://doi.org/10.1016/j.rcrx.2019.100010.

Carraresi, L., Berg, S., Bröring, S., 2018. Emerging value chains within the bioeconomy: structural changes in the case of phosphate recovery. J. Clean. Prod. 183, 87–101. https://doi.org/10.1016/j.jclepro.2018.02.135.

Chen, L., Chen, X.L., Zhou, C.H., Yang, H.M., Ji, S.F., Tong, D.S., Zhong, Z.K., Yu, W.H., Chu, M.Q., 2017. Environmental-friendly montmorillonite-biochar composites: facile production and tunable adsorption-release of ammonium and phosphate. J. Clean. Prod. 156, 648–659. https://doi.org/10.1016/j.jclepro.2017.04.050.

Chen, Q., Qin, J., Sun, P., Cheng, Z., Shen, G., 2018. Cow dung-derived engineered biochar for reclaiming phosphate from aqueous solution and its validation as slow-release fertilizer in soil-crop system. J. Clean. Prod. 172, 2009–2018. https://doi.org/10.1016/j.jclepro.2017.11.224.

Cheuyglintase, S., Hanly, J.A., Horne, D.J., 2018. Assessing the agronomic effectiveness of wastewater-treated Allophanic soil as a phosphorus source for plant growth. Soil Use Manag. 34, 472–478. https://doi.org/10.1111/sum.12461.

Chintala, R., Schumacher, T.E., McDonald, L.M., Clay, D.E., Malo, D.D., Papiernik, S.K., Clay, S.A., Julson, J.L., 2013. Phosphorus sorption and availability from biochars and soil/biochar mixtures. Clean 42, 626–634. https://doi.org/10.1002/clen.201300089.

Codling, E.E., Mulchi, C.L., Chaney, R.L., 2007. Grain yield and mineral element composition of maize grown on high phosphorus soils amended with water treatment residual. J. Plant Nutr. 30, 225–240. https://doi.org/10.1080/01904160601117937.

Courtney, R.G., Jordan, S.N., Harrington, T., 2009. Physicochemical changes in bauxite residue following application of spent mushroom compost and gypsum. Land Degrad. Dev. 20, 572–581.

Cucarella, V., Mazurek, R., Zaleski, T., Kopeć, M., Renman, G., 2009. Effect of Polonite used for phosphorus removal from wastewater on soil properties and fertility of a mountain meadow. Environ. Pollut. 157, 2147–2152. https://doi.org/10.1016/j.envpol.2009.02.007.

Cucarella, V., Renman, G., 2009. Phosphorus sorption capacity of filter materials used for on-site wastewater treatment determined in batch experiments–A comparative study. J. Environ. Qual. 38, 381. https://doi.org/10.2134/jeq2008.0192.

Cucarella, V., Zaleski, T., Mazurek, R., Renman, G., 2008. Effect of reactive substrates used for the removal of phosphorus from wastewater on the fertility of acid soils. Bioresour. Technol. 99, 4308–4314. https://doi.org/10.1016/j.biortech.2007.08.037.

Cucarella, V., Zaleski, T., Mazurek, R., Renman, G., 2007. Fertilizer potential of calcium-rich substrates used for phosphorus removal from wastewater. Pol. J. Environ. Stud. 16, 817–822.

Cusack, P.B., Callery, O., Courtney, R., Ujaczki, É., O'Donoghue, L.M.T., Healy, M.G., O'Donoghue, L.M.T., Healy, M.G., 2019. The use of rapid, small-scale column tests to determine the efficiency of bauxite residue as a low-cost adsorbent in the removal of dissolved reactive phosphorus from agricultural waters. J. Environ. Manag. 241, 273–283. https://doi.org/10.1016/j.jenvman.2019.04.042.

Dassanayake, K.B., Jayasinghe, G.Y., Surapaneni, A., Hetherington, C., 2015. A review on alum sludge reuse with special reference to agricultural applications and future challenges. Waste Manag. 38, 321–335. https://doi.org/10.1016/j.wasman.2014.11.025.

Del Bubba, M., Arias, C.A., Brix, H., 2003. Phosphorus adsorption maximum of sands for use as media in subsurface flow constructed reed beds as measured by the Langmuir isotherm. Water Res. 37, 3390–3400. https://doi.org/10.1016/S0043-1354(03)00231-8.

Deng, Y., Wheatley, A., 2018. Mechanisms of phosphorus removal by recycled crushed concrete. Int. J. Environ. Res. Publ. Health 15. https://doi.org/10.3390/ijerph15020357.

Dobbie, K.E., Heal, K.V., Smith, K.A., 2005. Assessing the performance of phosphorus-saturated ochre as a fertilizer and its environmental acceptability. Soil Use Manag. 21, 231–239. https://doi.org/10.1111/j.1475-2743.2005.tb00129.x.

Dobbie, K.E., Heal, K.V., Aumônier, J., Smith, K.A., Johnston, A., Younger, P.L., 2009. Evaluation of iron ochre from mine drainage treatment for removal of phosphorus from wastewater. Chemosphere 75, 795–800. https://doi.org/10.1016/j.chemosphere.2008.12.049.

Drizo, A., Cummings, J., Weber, D., Twohig, E., Druschel, G., Bourke, B., 2008. New evidence for rejuvenation of phosphorus retention capacity in EAF steel slag. Environ. Sci. Technol. 42, 6191–6197. https://doi.org/10.1021/es800232r.

Drizo, A., Frost, C.A., Grace, J., Smith, K.A., 1999. Physico-chemical screening of phosphate-removing substrates for use in constructed wetland systems. Water Res. 33, 3595–3602. https://doi.org/10.1016/S0043-1354(99)00082-2.

European Aluminium, 2015. Bauxite residue management: best practice [WWW Document]. http://www.world-aluminium.org/media/filer_public/2015/10/15/bauxite_residue_management_-_best_practice_english_oct15edit.pdf. accessed 8.6.19.

European Commission, 2019. Construction and demolition waste (CDW) [WWW Document]. Environment. https://ec.europa.eu/environment/waste/construction_demolition.htm. accessed 7.3.19.

European Commission (DG ENV), 2011. Service contract on management of construction and demolition waste – SR1 [WWW Document]. https://ec.europa.eu/environment/waste/pdf/2011_CDW_Report.pdf. accessed 7.3.19.

Euroslag, 2019. Statistics 2016 [WWW Document]. https://www.euroslag.com/. accessed 11.28.19.

Eurostat, 2019a. Environmental data centre on waste [WWW Document]. Environment. https://ec.europa.eu/environment/waste/index.htm. accessed 8.16.19.

Eurostat, 2019b. Environmental data centre [WWW Document]. https://ec.europa.eu/eurostat/data/database. accessed 8.16.19.

Evans, K., 2016. The history, challenges, and new developments in the management and use of bauxite residue. J. Sustain. Metall. 2, 316–331. https://doi.org/10.1007/s40831-016-0060-x.

Everaert, M., Warrinnier, R., Baken, S., Gustafsson, J.P., De Vos, D., Smolders, E., 2016. Phosphate-exchanged Mg-Al layered double hydroxides: a new slow release phosphate fertilizer. ACS Sustain. Chem. Eng. 4, 4280–4287. https://doi.org/10.1021/acssuschemeng.6b00778.

Ezzati, G., Healy, M.G., Christianson, L., Feyereisen, G.W., Thornton, S., Daly, K., Fenton, O., 2019. Developing and validating a decision support tool for media selection to mitigate drainage waters. Ecol. Eng. X 2. https://doi.org/10.1016/j.ecoena.2019.100010.

Fehily Timoney & Company, 2009. Codes of good practice for the use of biosolids in agriculture [WWW Document]. https://www.housing.gov.ie/file/2572. accessed 4.1.20.

Fenton, O., Healy, M.G., Rodgers, M., 2009. Use of ochre from an abandoned metal mine in the South east of Ireland for phosphorus sequestration from dairy dirty water. J. Environ. Qual. 38, 1120. https://doi.org/10.2134/jeq2008.0227.

Fenton, O., Serrenho, A., Healy, M.G., 2011. Evaluation of amendments to control phosphorus losses in runoff from dairy-soiled water. Water Air Soil Pollut. 222, 185–194. https://doi.org/10.1002/clen.201100206.

Filtralite, 2019. Filtralite® nature P 0,5-4 [WWW Document]. https://filtralite.com/en/products/filtraliter-nature-p-05-4. accessed 11.22.19.

Food and Agriculture Organization, 2019. FAOSTAT [WWW Document]. http://faostat3.fao.org/home/E. accessed 8.16.19.

Gaind, S., Gaur, A.C., 2002. Impact of fly ash and phosphate solubilising bacteria on soybean productivity. Bioresour. Technol. 85, 313–315. https://doi.org/10.1016/S0960-8524(02)00088-3.

Ganrot, Z., 2012. Use of zeolites for improved nutrient recovery from decentralized domestic wastewater. Handb. Nat. Zeolites 410–435. https://doi.org/10.2174/978160805261511201010410.

George, D.B., Berk, S.G., Adams, V.D., Ting, R.S., Roberts, R.O., Parks, L.H., Lott, R.C., 1995. Toxicity of alum sludge extracts to a freshwater alga, protozoan, fish, and marine bacterium. Arch. Environ. Contam. Toxicol. 29, 149–158. https://doi.org/10.1007/BF00212964.

Grace, M.A., Clifford, E., Healy, M.G., 2016. The potential for the use of waste products from a variety of sectors in water treatment processes. J. Clean. Prod. 137, 788–802. https://doi.org/10.1016/j.jclepro.2016.07.113.

Grassi, M., Kaykioglu, G., Belgiorno, V., Lofrano, G., 2012. Removal of emerging contaminants from water and wastewater by adsorption process. In: Lofrano, G. (Ed.), Green Chemistry for Sustainability. SpringerBriefs, pp. 15–38. https://doi.org/10.1007/978-94-007-3916-1.

Guan, B., Yao, X., Jiang, J., Tian, Z., An, S., Gu, B., Cai, Y., 2009. Phosphorus removal ability of three inexpensive substrates: physicochemical properties and application. Ecol. Eng. 35, 576–581. https://doi.org/10.1016/j.ecoleng.2008.04.015.

Guaya, D., Valderrama, C., Farran, A., Sauras, T., Cortina, J.L., 2018. Valorisation of N and P from waste water by using natural reactive hybrid sorbents: nutrients (N,P,K) release evaluation in amended soils by dynamic experiments. Sci. Total Environ. 612, 728–738. https://doi.org/10.1016/j.scitotenv.2017.08.248.

Gupta, S., Babu, B.V., 2009. Modeling, simulation, and experimental validation for continuous Cr(VI) removal from aqueous solutions using sawdust as an adsorbent. Bioresour. Technol. 100, 5633–5640. https://doi.org/10.1016/j.biortech.2009.06.025.

Gustafsson, J.P., Renman, A., Renman, G., Poll, K., 2008. Phosphate removal by mineral-based sorbents used in filters for small-scale wastewater treatment. Water Res. 42, 189–197. https://doi.org/10.1016/j.watres.2007.06.058.

Harikishore Kumar Reddy, D., Vijayaraghavan, K., Kim, J.A., Yun, Y.S., 2017.

Valorisation of post-sorption materials: opportunities, strategies, and challenges. Adv. Colloid Interface Sci. 242, 35–58. https://doi.org/10.1016/j.cis.2016.12.002.

Healy, M.G., Burke, P., Rodgers, M., 2010. The use of laboratory sand, soil and crushed-glass filter columns for polishing domestic-strength synthetic wastewater that has undergone secondary treatment. J. Environ. Sci. Heal. - Part A Toxic/Hazardous Subst. Environ. Eng. 45, 1635–1641. https://doi.org/10.1080/10934529.2010.506130.

Hou, Q., Meng, P., Pei, H., Hu, W., Chen, Y., 2018. Phosphorus adsorption characteristics of alum sludge: adsorption capacity and the forms of phosphorus retained in alum sludge. Mater. Lett. 229, 31–35. https://doi.org/10.1016/j.matlet.2018.06.102.

Hua, G., Salo, M.W., Schmit, C.G., Hay, C.H., 2016. Nitrate and phosphate removal from agricultural subsurface drainage using laboratory woodchip bioreactors and recycled steel byproduct filters. Water Res. 102, 180–189. https://doi.org/10.1016/j.watres.2016.06.022.

Huang, Y.X., Liu, M.J., Chen, S., Jasmi, I.I., Tang, Y., Lin, S., 2019. Enhanced adsorption and slow release of phosphate by dolomite–alginate composite beads as potential fertilizer. Water Environ. Res. 797–804. https://doi.org/10.1002/wer.1122.

Hyde, J.E., Morris, T.F., 2004. Phosphorus availability from phosphorus-amended water treatment residual. Commun. Soil Sci. Plant Anal. 35, 1033–1046. https://doi.org/10.1081/CSS-120030579.

Hylander, L.D., Kietlińska, A., Renman, G., Simán, G., 2006. Phosphorus retention in filter materials for wastewater treatment and its subsequent suitability for plant production. Bioresour. Technol. 97, 914–921. https://doi.org/10.1016/j.biortech.2005.04.026.

Hylander, L.D., Simán, G., 2006. Phosphorus fractionation in soils and wastewater sorbent materials as an indicator of material specific and storage-dependant availability. Commun. Soil Sci. Plant Anal. 37, 1013–1030. https://doi.org/10.1080/00103620600584362.

Hylander, L.D., Simán, G., 2001. Plant availability of phosphorus sorbed to potential wastewater treatment materials. Biol. Fertil. Soils 34, 42–48. https://doi.org/10.1007/s003740100369.

Ippolito, J.A., Barbarick, K.A., Elliott, H.A., 2011. Drinking water treatment residuals: a review of recent uses. J. Environ. Qual. 40, 1. https://doi.org/10.2134/jeq2010.0242.

Ippolito, J.A., Barbarick, K.A., Stromberger, M.E., Paschke, M.W., Brobst, R.B., 2009. Water treatment residuals and biosolids long-term co-applications effects to semi-arid grassland soils and vegetation. Soil Sci. Soc. Am. J. 73, 1880–1889. https://doi.org/10.2136/sssaj2008.0352.

James, B.R., Rabenhorst, M.C., Frigon, G.A., 1992. Phosphorus sorption by peat and sand amended with iron oxides or steel wool. Water Environ. Res. 64, 699–705. https://doi.org/10.2175/WER.64.5.6.

Jarvie, H.P., Flaten, D., Sharpley, A.N., Kleinman, P.J.A., Healy, M.G., King, S.M., 2019. Future phosphorus: advancing new 2D phosphorus allotropes and growing a sustainable bioeconomy. J. Environ. Qual. 48, 1145–1155. https://doi.org/10.2134/jeq2019.03.0135.

Jellali, S., Wahab, M.A., Hassine, R. Ben, Hamzaoui, A.H., Bousselmi, L., 2011. Adsorption characteristics of phosphorus from aqueous solutions onto phosphate mine wastes. Chem. Eng. J. 169, 157–165. https://doi.org/10.1016/j.cej.2011.02.076.

Jenssen, P.D., Krogstad, T., Paruch, A.M., Mæhlum, T., Adam, K., Arias, C.A., Heistad, A., Jonsson, L., Hellström, D., Brix, H., Yli-Halla, M., Vråle, L., Valve, M., 2010. Filter bed systems treating domestic wastewater in the Nordic countries - performance and reuse of filter media. Ecol. Eng. 36, 1651–1659. https://doi.org/10.1016/j.ecoleng.2010.07.004.

Kang, K., Lee, C.G., Choi, J.W., Hong, S.G., Park, S.J., 2017. Application of thermally treated crushed concrete granules for the removal of phosphate: a cheap adsorbent with high adsorption capacity. Water Air Soil Pollut. 228 https://doi.org/10.1007/s11270-016-3196-1.

Karunarathna, M.H.J.S., Hatten, Z.R., Bailey, K.M., Lewis, E.T., Morris, A.L., Kolk, A.R., Laib, J.C., Tembo, N., Williams, R.A., Phillips, B.T., Ash, B.L., Midden, W.R., Ostrowski, A.D., 2019. Reclaiming phosphate from waste solutions with Fe(III)-Polysaccharide hydrogel beads for photo-controlled-release fertilizer. J. Agric. Food Chem. 67, 12155–12163. https://doi.org/10.1021/acs.jafc.9b02860.

King'ori, A.M., 2011. A Review of the uses of poultry eggshells and shell membranes. Int. J. Poultry Sci. 10, 908–912. https://doi.org/10.3923/ijps.2011.908.912.

Kõiv, M., Ostonen, I., Vohla, C., Mõtlep, R., Liira, M., Lõhmus, K., Kirsimäe, K., Mander, Ü., 2012. Reuse potential of phosphorus-rich filter materials from subsurface flow wastewater treatment filters for forest soil amendment. Hydrobiologia 692, 145–156. https://doi.org/10.1007/s10750-011-0944-5.

Kõiv, M., Vohla, C., Mõtlep, R., Liira, M., Kirsimäe, K., Mander, Ü., 2009. The performance of peat-filled subsurface flow filters treating landfill leachate and municipal wastewater. Ecol. Eng. 35, 204–212. https://doi.org/10.1016/j.ecoleng.2008.04.006.

Kong, L., Tian, Y., Wang, Y., Li, N., Liu, Y., Pang, Z., Huang, X., Li, M., Zhang, J., Zuo, W., 2019. Periclase-induced generation of flowerlike clay-based layered double hydroxides: a highly efficient phosphate scavenger and solid-phase fertilizer. Chem. Eng. J. 359, 902–913. https://doi.org/10.1016/j.cej.2018.11.007.

Köse, T.E., Kivanç, B., 2011. Adsorption of phosphate from aqueous solutions using calcined waste eggshell. Chem. Eng. J. 178, 34–39. https://doi.org/10.1016/j.cej.2011.09.129.

Kvarnström, M.E., Morel, C.A.L., Krogstad, T., 2004. Plant-availability of phosphorus in filter substrates derived from small-scale wastewater treatment systems. Ecol. Eng. 22, 1–15. https://doi.org/10.1016/j.ecoleng.2003.12.005.

LECA, 2019. LECA lightweight expanded clay aggregate [WWW Document]. https://www.leca.co.uk/further-solutions/. accessed 8.12.19.

Li, R., Wang, J.J., Zhang, Z., Awasthi, M.K., Du, D., Dang, P., Huang, Q., Zhang, Y., Wang, L., 2018. Recovery of phosphate and dissolved organic matter from aqueous solution using a novel CaO-MgO hybrid carbon composite and its feasibility in phosphorus recycling. Sci. Total Environ. 642, 526–536. https://doi.org/10.1016/j.scitotenv.2018.06.092.

Li, R., Wang, J.J., Zhou, B., Awasthi, M.K., Ali, A., Zhang, Z., Lahori, A.H., Mahar, A., 2016. Recovery of phosphate from aqueous solution by magnesium oxide decorated magnetic biochar and its potential as phosphate-based fertilizer substitute. Bioresour. Technol. 215, 209–214. https://doi.org/10.1016/j.biortech.2016.02.125.

Li, Y., Liu, C., Luan, Z., Peng, X., Zhu, C., Chen, Z., Zhang, Z., Fan, J., Jia, Z., 2006. Phosphate removal from aqueous solutions using raw and activated red mud and fly ash. J. Hazard Mater. 137, 374–383. https://doi.org/10.1016/j.jhazmat.2006.02.011.

Litaor, M.I., Schechter, S., Zohar, I., Massey, M.S., Ippolito, J.A., 2019. Making phosphorus fertilizer from dairy wastewater with aluminum water treatment residuals. Soil Sci. Soc. Am. J. 83, 649–657. https://doi.org/10.2136/sssaj2018.07.0278.

Liu, H., 2016. Achilles heel of environmental risk from recycling of sludge to soil as amendment: a summary in recent ten years (2007–2016). Waste Manag. 56, 575–583. https://doi.org/10.1016/j.wasman.2016.05.028.

Liu, M., Liang, Z., Yang, F., Ma, H., Huang, L., Wang, M., 2010. Impacts of sand amendment on rice (*Oryza sativa* L.) growth and yield in saline-sodic soils of North-East China. J. Food, Agric. Environ. Times 8, 412–418.

Liu, X., Shen, F., Qi, X., 2019. Adsorption recovery of phosphate from aqueous solution by CaO-biochar composites prepared from eggshell and rice straw. Sci. Total Environ. 666, 694–702. https://doi.org/10.1016/j.scitotenv.2019.02.227.

Liu, Y., Naidu, R., Ming, H., 2011. Red mud as an amendment for pollutants in solid and liquid phases. Geoderma 163, 1–12. https://doi.org/10.1016/j.geoderma.2011.04.002.

Lukashe, N.S., Mupambwa, H.A., Green, E., Mnkeni, P.N.S., 2019. Inoculation of fly ash amended vermicompost with phosphate solubilizing bacteria (*Pseudomonas fluorescens*) and its influence on vermi-degradation, nutrient release and biological activity. Waste Manag. 83, 14–22. https://doi.org/10.1016/j.wasman.2018.10.038.

Malik, A., Thapliyal, A., 2009. Eco-friendly fly ash utilization: potential for land application. Crit. Rev. Environ. Sci. Technol. https://doi.org/10.1080/10643380701413690.

Marhual, N.P., Pradhan, N., Mohanta, N.C., Sukla, L.B., Mishra, B.K., 2011. Dephosphorization of LD slag by phosphorus solubilising bacteria. Int. Biodeterior. Biodegrad. 65, 404–409. https://doi.org/10.1016/j.ibiod.2011.01.003.

Mateus, D.M.R., Vaz, M.M.N., Pinho, H.J.O., 2012. Fragmented limestone wastes as a constructed wetland substrate for phosphorus removal. Ecol. Eng. 41, 65–69. https://doi.org/10.1016/j.ecoleng.2012.01.014.

McCoy, E.L., 1998. Sand and organic amendment influences on soil physical properties related to turf establishment. Agron. J. 90, 411–419.

Misaelides, P., 2011. Application of natural zeolites in environmental remediation: a short review. Microporous Mesoporous Mater. 144, 15–18. https://doi.org/10.1016/j.micromeso.2011.03.024.

Mitrogiannis, D., Psychoyou, M., Koukouzas, N., Tsoukalas, N., Palles, D., Kamitsos, E., Pantazidis, A., Oikonomou, G., Baziotis, I., 2018. Phosphate recovery from real fresh urine by $Ca(OH)_2$ treated natural zeolite. Chem. Eng. J. 347, 618–630. https://doi.org/10.1016/j.cej.2018.04.102.

Mohajerani, A., Vajna, J., Cheung, T.H.H., Kurmus, H., Arulrajah, A., Horpibulsuk, S., 2017. Practical recycling applications of crushed waste glass in construction materials: a review. Construct. Build. Mater. 156, 443–467. https://doi.org/10.1016/j.conbuildmat.2017.09.005.

Mohan, D., Sarswat, A., Ok, Y.S., Pittman, C.U., 2014. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent - a critical review. Bioresour. Technol. 160, 191–202. https://doi.org/10.1016/j.biortech.2014.01.120.

Motz, H., Geiseler, J., 2001. Products of steel slags an opportunity to save natural resources. Waste Manag. 21, 285–293. https://doi.org/10.1016/S0956-053X(00)00102-1.

Naghizadeh, A., Kalantary, R., Rashidi, A., Mahvi, A., Nabizadeh, R., Nasseri, S., 2013. Continuous adsorption of natural organic matters in a column packed with carbon nanotubes. J. Environ. Heal. Sci. Eng. 11, 14. https://doi.org/10.1186/2052-336x-11-14.

Nakazawa, R., Tomemori, H., Hirano, A., Mochizuki, H., An, P., Inanaga, S., 2006. Effects of the application of porous glass material treated with phosphate on the growth of tomato plants and the phyto-available phosphate in soil. Soil Sci. Plant Nutr. 52, 540–544. https://doi.org/10.1111/j.1747-0765.2006.00057.x.

Ning, D., Song, A., Fan, F., Li, Z., Liang, Y., 2014. Effects of slag-based silicon fertilizer on rice growth and brown-spot resistance. PLoS One 9, 1–9. https://doi.org/10.1371/journal.pone.0102681.

Oladeji, O.O., Sartain, J.B., O'Connor, G.A., 2006. Agronomic impact of water treatment residual Co-applied with phosphorus sources to Florida. Soil Crop Sci. Soc. Florida 65, 38–48. https://doi.org/10.1116/1.573012.

Paruch, A.M., Krogstad, T., Jenssen, P.D., 2007. Application of used wetland filter media in agriculture - control of heavy metal contents and faecal contamination. Ecohydrol. Hydrobiol. 7, 243–253. https://doi.org/10.1016/S1642-3593(07)70107-6.

Penn, C., Chagas, I., Klimeski, A., Lyngsie, G., 2017. A review of phosphorus removal structures: how to assess and compare their performance. Water 9, 1–22. https://doi.org/10.3390/w9080583.

Penn, C.J., Bryant, R.B., Kleinman, P.J., Allen, A.L., 2007. Removing dissolved phosphorus from drainage ditch water with phosphorus sorbing materials. J. Soil Water Conserv. 62, 269–276.

Piol, M.N., Paricoto, M., Saralegui, A.B., Basack, S., Vullo, D., Boeykens, S.P., 2019. Dolomite used in phosphate water treatment: desorption processes, recovery, reuse and final disposition. J. Environ. Manag. 237, 359–364. https://doi.org/10.1016/j.jenvman.2019.02.085.

Proctor, D.M., Fehling, K.A., Shay, E.C., Wittenborn, J.L., Green, J.J., Avent, C., Bigham, R.D., Connolly, M., Lee, B., Shepker, T.O., Zak, M.A., 2000. Physical and chemical characteristics of blast furnace, basic oxygen furnace, and electric arc furnace steel industry slags. Environ. Sci. Technol. 34, 1576–1582. https://doi.org/10.1021/es9906002.

Qiao, W., Bai, H., Tang, T., Miao, J., Yang, Q., 2019. Recovery and utilization of phosphorus in wastewater by magnetic Fe_3O_4/Zn-Al-Fe-La layered double hydroxides (LDHs). Colloids Surfaces A Physicochem. Eng. Asp. 577, 118–128. https://doi.org/10.1016/j.colsurfa.2019.05.046.

Ram, L.C., Masto, R.E., 2014. Fly ash for soil amelioration: a review on the influence of ash blending with inorganic and organic amendments. Earth Sci. Rev. 128, 52–74. https://doi.org/10.1016/j.earscirev.2013.10.003.

Renman, A., Renman, G., Gustafsson, J.P., Hylander, L., 2009. Metal removal by bed filter materials used in domestic wastewater treatment. J. Hazard Mater. 166, 734–739. https://doi.org/10.1016/j.jhazmat.2008.11.127.

Rittmann, B.E., Mayer, B., Westerhoff, P., Edwards, M., 2011. Capturing the lost phosphorus. Chemosphere 84, 846–853. https://doi.org/10.1016/j.chemosphere.2011.02.001.

Rutledge, S.O., Gagnon, G.A., 2002. Comparing crushed recycled glass to silica sand for dual media filtration. J. Environ. Eng. Sci. 1, 349–358. https://doi.org/10.1139/S02-023.

Saadi, Z., Saadi, R., Fazaeli, R., 2013. Fixed-bed adsorption dynamics of Pb (II) adsorption from aqueous solution using nanostructured γ-alumina. J. Nanostruct. Chem. 3, 48. https://doi.org/10.1186/2193-8865-3-48.

Sakadevan, K., Bavor, H.J., 1998. Phosphate adsorption characteristics of soils, slags and zeolite to be used as substrates in constructed wetland systems. Water Res. 32, 393–399. https://doi.org/10.1016/S0043-1354(97)00271-6.

Sapsford, D., Santonastaso, M., Thorn, P., Kershaw, S., 2015. Conversion of coal mine drainage ochre to water treatment reagent: production, characterisation and application for P and Zn removal. J. Environ. Manag. 160, 7–15. https://doi.org/10.1016/j.jenvman.2015.06.004.

Seshadri, B., Bolan, N.S., Kunhikrishnan, A., 2013. Effect of clean coal combustion products in reducing soluble phosphorus in soil I. Adsorption study. Water Air Soil Pollut. 224 https://doi.org/10.1007/s11270-013-1524-2.

Shepherd, J.G., Sohi, S.P., Heal, K.V., 2016. Optimising the recovery and re-use of phosphorus from wastewater effluent for sustainable fertiliser development. Water Res. 94, 155–165. https://doi.org/10.1016/j.watres.2016.02.038.

Smadi, M.M., Haddad, R.H., 2003. The use of oil shale ash in Portland cement concrete. Cement Concr. Compos. 25, 43–50. https://doi.org/10.1016/S0958-9465(01)00054-3.

Sønderup, M.J., Egemose, S., Bochdam, T., Flindt, M.R., 2015. Treatment efficiency of a wet detention pond combined with filters of crushed concrete and sand: a Danish full-scale study of stormwater. Environ. Monit. Assess. 187, 1–18. https://doi.org/10.1007/s10661-015-4975-7.

Sønderup, M.J., Egemose, S., Hoffmann, C.C., Reitzel, K., Flindt, M.R., 2014. Modeling phosphorus removal in wet ponds with filter zones containing sand or crushed concrete. Ecol. Eng. 66, 52–62. https://doi.org/10.1016/j.ecoleng.2013.06.003.

Teagasc, 2016. In: Major and Micro Nutrient Advice for Productive Agricultural Crops, fourth ed. Teagasc, Oak Park, Co. Carlow.

Turner, T., Wheeler, R., Stone, A., Oliver, I., 2019. Potential alternative reuse pathways for water treatment residuals: remaining barriers and questions—a review. Water Air Soil Pollut. 230 https://doi.org/10.1007/s11270-019-4272-0.

Urvashi, Masto, R.E., Selvi, V.A., Ram, L.C., Srivastava, N.K., 2007. An international study: effect of farm manure on the release of phosphorus from fly ash. Remediation 17, 69–81. https://doi.org/10.1002/rem.20144.

Vohla, C., Kõiv, M., Bavor, H.J., Chazarenc, F., Mander, Ü., 2011. Filter materials for phosphorus removal from wastewater in treatment wetlands — a review. Ecol. Eng. 37, 70–89. https://doi.org/10.1016/j.ecoleng.2009.08.003.

Wang, S., Ma, M., Zhang, Q., Sun, G., Jiao, T., Okazaki, R.K., 2015. Efficient phosphate sequestration in waters by the unique hierarchical 3D artemia egg shell supported nano-$Mg(OH)_2$ composite and sequenced potential application in slow release fertilizer. ACS Sustain. Chem. Eng. 3, 2496–2503. https://doi.org/10.1021/acssuschemeng.5b00594.

Wang, S., Peng, Y., 2010. Natural zeolites as effective adsorbents in water and wastewater treatment. Chem. Eng. J. 156, 11–24. https://doi.org/10.1016/j.cej.2009.10.029.

Wang, X., Cai, Q.S., 2006. Steel slag as an iron fertilizer for corn growth and soil improvement in a pot experiment. Pedosphere 16, 519–524. https://doi.org/10.1016/S1002-0160(06)60083-0.

Wendling, L.A., Blomberg, P., Sarlin, T., Priha, O., Arnold, M., 2013. Phosphorus sorption and recovery using mineral-based materials: sorption mechanisms and potential phytoavailability. Appl. Geochem. 37, 157–169. https://doi.org/10.1016/j.apgeochem.2013.07.016.

Withers, P.J.A., Elser, J.J., Hilton, J., Ohtake, H., Schipper, W.J., Van Dijk, K.C., 2015. Greening the global phosphorus cycle: how green chemistry can help achieve planetary P sustainability. Green Chem. 17, 2087–2099. https://doi.org/10.1039/c4gc02445a.

Xiong, J.B., Mahmood, Q., 2010. Adsorptive removal of phosphate from aqueous media by peat. Desalination 259, 59–64. https://doi.org/10.1016/j.desal.2010.04.035.

Yang, Y., Tomlinson, D., Kennedy, S., Zhao, Y.Q., 2006. Dewatered alum sludge: a potential adsorbent for phosphorus removal. Water Sci. Technol. 54, 207–213. https://doi.org/10.2166/wst.2006.564.

Yang, Y., Zhao, Y.Q., Kearney, P., 2008. Influence of ageing on the structure and phosphate adsorption capacity of dewatered alum sludge. Chem. Eng. J. 145, 276–284. https://doi.org/10.1016/j.cej.2008.04.026.

Yao, Y., Gao, B., Chen, J., Yang, L., 2013. Engineered biochar reclaiming phosphate from aqueous solutions: mechanisms and potential application as a slow-release fertilizer. Environ. Sci. Technol. 47, 8700–8708. https://doi.org/10.1021/es4012977.

Yao, Y., Gao, B., Inyang, M., Zimmerman, A.R., Cao, X., Pullammanappallil, P., Yang, L., 2011. Removal of phosphate from aqueous solution by biochar derived from anaerobically digested sugar beet tailings. J. Hazard Mater. 190, 501–507. https://doi.org/10.1016/j.jhazmat.2011.03.083.

Yao, Y., Gao, B., Zhang, M., Inyang, M., Zimmerman, A.R., 2012. Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. Chemosphere 89, 1467–1471. https://doi.org/10.1016/j.chemosphere.2012.06.002.

Yildirim, I.Z., Prezzi, M., 2011. Chemical, mineralogical, and morphological properties of steel slag. Adv. Civ. Eng. 2011, 1–13. https://doi.org/10.1155/2011/463638.

Zhang, W., Brown, G.O., Storm, D.E., Zhang, H., 2008. Fly-ash-amended sand as filter media in bioretention cells to improve phosphorus removal. Water Environ. Res. 80, 507–516. https://doi.org/10.2175/106143008X266823.

Zhao, Y., Liu, R., Awe, O.W., Yang, Y., Shen, C., 2018. Acceptability of land application of alum-based water treatment residuals – an explicit and comprehensive review. Chem. Eng. J. 353, 717–726. https://doi.org/10.1016/j.cej.2018.07.143.

Zohar, I., Ippolito, J.A., Massey, M.S., Litaor, I.M., 2017. Innovative approach for recycling phosphorous from agrowastewaters using water treatment residuals (WTR). Chemosphere 168, 234–243.

Zohar, I., Massey, M.S., Ippolito, J.A., Litaor, M.I., 2018. Phosphorus sorption characteristics in aluminum-based water treatment residuals reacted with dairy wastewater: 1. Isotherms, XRD, and SEM-EDS analysis. J. Environ. Qual. 47, 538. https://doi.org/10.2134/jeq2017.10.0405.