UHI Research Database pdf download summary

From molecular to large-scale phosphorous recovery from wastewater using cost-effective adsorbents

Pap, Sabolc; Turk Sekulic, Maja; Bremner, Barbara; Taggart, Mark A.

Published in:
Integrated and Hybrid Process Technology for Water and Wastewater Treatment

Publication date:
2021

Publisher rights:
Copyright © 2021 Elsevier Inc. All rights reserved.

The re-use license for this item is:
CC BY-NC-ND

The Document Version you have downloaded here is:
Peer reviewed version

The final published version is available direct from the publisher website at:
10.1016/B978-0-12-823031-2.00025-2

Link to author version on UHI Research Database

Citation for published version (APA):
Pap, S., Turk Sekulic, M., Bremner, B., & Taggart, M. A. (2021). From molecular to large-scale phosphorous recovery from wastewater using cost-effective adsorbents: An integrated approach. In *Integrated and Hybrid Process Technology for Water and Wastewater Treatment* (pp. 61-85). Elsevier. https://doi.org/10.1016/B978-0-12-823031-2.00025-2

General rights
Copyright and moral rights for the publications made accessible in the UHI Research Database are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights:

1) Users may download and print one copy of any publication from the UHI Research Database for the purpose of private study or research.
2) You may not further distribute the material or use it for any profit-making activity or commercial gain
3) You may freely distribute the URL identifying the publication in the UHI Research Database

Take down policy
If you believe that this document breaches copyright please contact us at RO@uhi.ac.uk providing details; we will remove access to the work immediately and investigate your claim.

Download date: 04. Jun. 2023

From molecular to large-scale phosphorus recovery from wastewater using cost-effective adsorbents: an integrated approach

Sabolc Pap[a,b], Maja Turk Sekulic[b], Barbara Bremner[a], Mark A. Taggart[a]

[a]*Environmental Research Institute, North Highland College, University of the Highlands and Islands, Castle Street, Thurso, KW14 7JD, UK*

[b]*University of Novi Sad, Faculty of Technical Sciences, Department of Environmental Engineering and Occupational Safety and Health, Trg Dositeja Obradovića 6, 21 000 Novi Sad, Serbia*

Abstract

Phosphorus (P) recovery from wastewater will become increasingly vital in the future in terms of the protection of valuable freshwater resources (i.e., from eutrophication) and due to rapidly dwindling terrestrial rock phosphate stocks. Effective management of P as a critical resource will require new integrated approaches and techniques to efficiently recover P from wastewater (liquid phase), ideally in a form that can be readily used in agriculture for fertiliser. This chapter will present a comparative review of the performance of adsorbents, adsorption mechanisms, desorption and P plant availability potential regarding cost-effective adsorbents synthesised within the principles of a more ‘circular economy’. In addition, considerations regarding scale-up, technique costs and legislative perspectives will be explored with respect to large-scale P recovery systems. Finally, to encourage further applied P-recovery based research, several adsorption case studies at pilot-, full- and large-scale using integrated-hybrid P removal systems (e.g., membrane/adsorbent reactors, biological nutrient removal with tertiary reactive media adsorption, algal hybrid processes) will be highlighted, while noting key knowledge gaps and future priorities in this field.

Keywords

Wastewater treatment; Adsorption; Critical resource management; Secondary P fertiliser; Circular economy; Nutrient recovery; Integrated P removal; Hybrid processes.

Introduction

Phosphorus (P) is an essential element within agriculture (as a key fertiliser component) and within other industries (i.e., food, metallurgical and chemical). The dominant source of terrestrial P (i.e., for fertilisers) comes from rapidly dwindling terrestrial rock phosphate reserves (Ehmann, Bach, Laopeamthong, Bilbao, & Lewandowski, 2017). Over the last 10 years, the global price of rock phosphate has fluctuated by ~800% (~$50/t to ~$400/t) and is expected to increase exponentially in the next 20 years (Shepherd, Kleemann, et al., 2016). Schröder et al. (2011) estimated that by 2035, global P demand will exceed supply. This challenge could be mitigated (at least in part) by greater use and recovery of P from various waste streams (e.g., sewage sludge, solid waste, wastewater), however in many countries (i.e., in European Union - EU) this practice is restricted by legislation due to potential environmental risks posed by organic/inorganic pollutants and pathogens which may be present. Shepherd et al. (2016b) described the paradoxical nature of this problem whereby both a problematic scarcity and a detrimental profusion of P exists in different parts of the same system. In other words, P loss exists within all parts of human society, and finding solutions to better recycle/recover (within the same system) holds the answer.

Municipal wastewater is a promising and viable source of P. Its recovery would help to re-establish a more ‘circular economy’; to extract maximum value from waste and help to enhance resource consumption (Lukas Egle, Rechberger, & Zessner, 2015). Within this foundation, a new model in wastewater treatment could be established, with so called '*waste to resource'* or *'waste to crop'* becoming the norm. While the wastewater solid phase (e.g., sludge and sludge ashes) generally holds much higher P (which can be extracted through bioleaching, wet-chemical extraction or thermal hydrolysis), significant recent work has focused on developing novel technologies to exploit the liquid phase (Chrispim, Scholz, & Nolasco, 2019). This approach would help address often strict P environmental discharge requirements (i.e., 0.05 and 0.01 mg P/L discharge limits for sensitive lakes, rivers or reservoirs in EU, USA, Canada, Australia (Solovchenko, Verschoor, Jablonowski, & Nedbal, 2016)) and help address P scarcity (Loganathan, Vigneswaran, Kandasamy, & Bolan, 2014). Different physico-chemical and biological methods have been applied to remove aqueous P, but many have certain limitations: i.e., are effective only at high P concentrations (biological methods), demonstrate low P selectivity (adsorption), involve large amounts of additional chemicals (chemical precipitation) or involve high capital, operational and energy costs (electrodialysis and membrane processes) (Vikrant et al., 2018). Of these, adsorption is often considered to be a cost-effective and efficient option because of the ease of process operation, simplicity of design, absence of additional waste production, economics and the capability to remove P even at low concentrations (Pap, Kirk, Bremner, Turk Sekulic, et al., 2020). Additionally, recovery of P through adsorption onto other waste materials or onto their activated forms (e.g., biochars, functionalised materials) may provide additional benefits. Ideally, this process would involve the generation of a value-added P-rich product, low in other undesirable adsorbed contaminants. In creating such an adsorbent/product, potential would then exist to use this directly as a secondary P fertiliser and/or soil amendment product. However, adsorption based P recovery needs integrated evaluation which considers multiple aspects, not least: the feasibility of moving from bench-scale to full scale implementation; plant availability of recovered P; the chemical/environmental 'quality' (safety) of the saturated adsorbent/product; and the environmental, logistical and economic reality of transitioning these new products into the market economy (i.e., implementation of Life-cycle assessment (LCA) and other tools). Further, adsorption alone will not be the only process at a wastewater treatment plant (WWTP), and there will likely need to be integrated connections between technologies. A better understanding of how to best integrate adsorption processes with other treatment techniques (to achieve the highest total P recovery/removal and create a clean P-rich product) is therefore crucial. Fig. 1 shows how an integrated set of treatment options also needs to be linked to a set of feasibility considerations to achieve integrated P recovery.

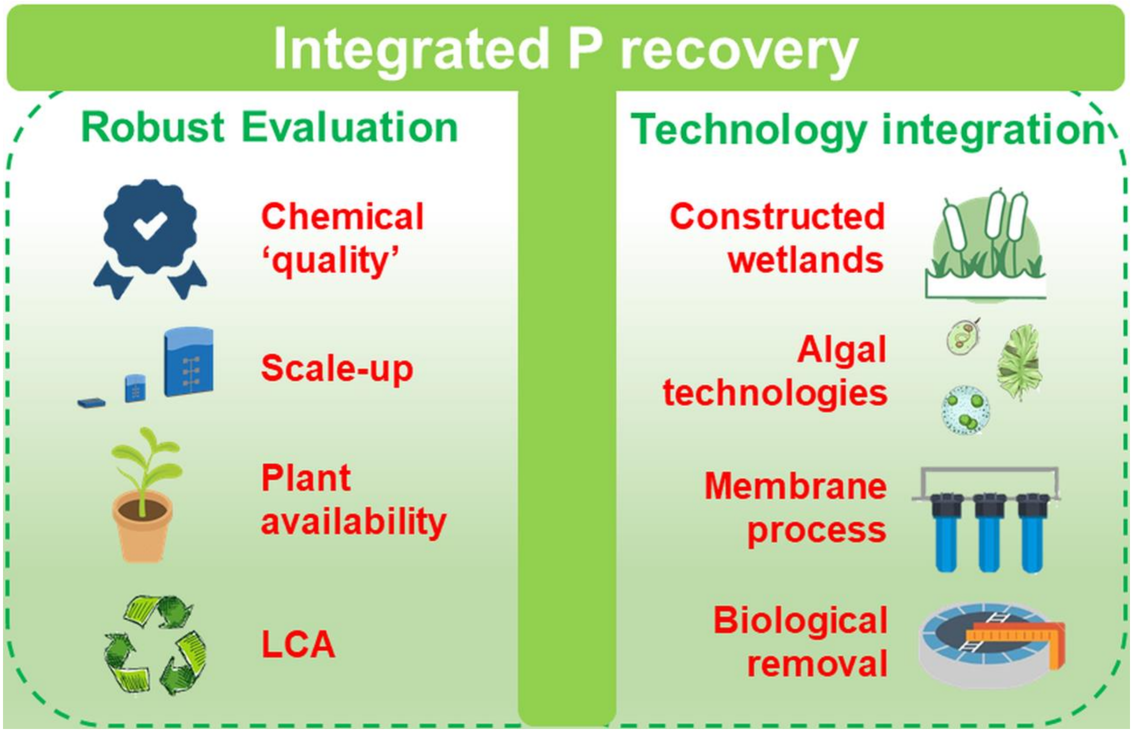

Fig. 1. Integrated P-recovery – schematic expressing how multiple treatment options potentially need to be linked to a set of key feasibility considerations to achieve sustainable integrated P recovery.

Low-cost adsorbents for P recovery from wastewater

In recent years, numerous adsorbents have been considered for their potential to remove P from wastewater, including: iron, aluminium, zirconium and rare earth metal oxides, hydroxides and oxyhydroxides (R. Liu et al., 2018; L. Wang et al., 2019), zerovalent iron (Bhattacharjee, Darwish, & Shanableh, 2020), calcium and magnesium carbonates and hydroxides (Loganathan et al., 2014), agricultural and industrial by-products (Muisa, Nhapi, Ruziwa, & Manyuchi, 2020), functionalised clay materials (Huang, Zhang, & Li, 2017), layered double hydroxides (LDH) (Bacelo, Pintor, Santos, Boaventura, & Botelho, 2020; Loganathan et al., 2014), polymers (Bacelo et al., 2020), anion-exchange resins (Song & Li, 2019), functionalised biochars and activated carbons (Vikrant et al., 2018; Yang et al., 2020; Yin, Zhang, Wang, & Zhao, 2017). Some of these showed very high adsorption capacity, relatively high selectivity, and excellent stability. However, the aforementioned adsorbents still had limitations in terms of their application – especially in terms of their production and implementation costs. Suresh Kumar et al. (2019) defined three important factors which governed the cost of P removal and recovery through adsorption. These were: (I) the adsorbent cost, (II) the practical loading possible (i.e., adsorption capacity within real (not ‘idealised’ lab-based) environmental conditions), and (III) the cost of regeneration. From the P recovery perspective, the final point (the regeneration cost) can be excluded assuming the P-loaded adsorbent could be simply used directly, i.e., as a fertiliser/soil amendment.

Among these factors, adsorbent cost can be considered the most important – which in turn, is governed by the precursors/chemicals used to create the adsorbent and the number of synthesis steps needed (Suresh Kumar et al., 2018). Three different categories could be proposed: i.e., *low cost* (≤$1000/t); *intermediate cost* (between $3000-6000/t); *high cost* (between $15000-20000/t) (Suresh Kumar et al., 2019). Of the afore mentioned adsorbents, only the calcium and magnesium-based waste materials, agricultural and industrial by-products, layered double hydroxides and biochars would belong to the low-cost category (based on production price). From these, biochars and various organic waste/by-products may show the highest potential for P recovery (see Table 1) with the added benefit of subsequent land utilisation (M. Zhang et al., 2020). Their physical-chemical properties (often with only minor modification/functionalisation to improve affinity toward P) would lend them (if low in other adsorbed contaminants) toward being re-used as P-enriched soil improver/fertiliser material (Tan, Lin, Ji, & Rainey, 2017; Yu et al., 2019). Recent studies have reported that converting existing agricultural residues and wastes into biochar may be a promising approach to sustainable crop management, maintaining nutrient availability and soil conservation (Y. Dai, Wang, Lu, Yan, & Yu, 2020). By way of example, Fig. 2 shows how waste brash from tree felling (undertaken in this case for peatland restoration) in Scotland could be used as a precursor for biochar production and the subsequent potential creation of a P-enriched fertiliser and/or soil C stabiliser.

Fig. 2. 'Circular economy' based approach – involving the utilisation of waste wood brash (created following tree felling during peatland restoration) to create a biochar that could then be P-enriched and used as a fertiliser in new forestry (or remain as a soil C stabiliser)

Adsorption capacity, as the second key important factor in P removal/recovery cost, is a function of adsorbent characteristics (i.e., surface chemistry and area), as well as the physico-chemical characteristics of the liquid phase/wastewater (i.e., pH, concentration of P and presence of other competing ions/molecules) (Bacelo et al., 2020). Additionally, interaction mechanisms during adsorption greatly affect adsorption performance, and therefore must be taken into consideration. Interaction mechanisms between adsorbents and P are typically categorised as: *surface interactions* which include hydrogen bonding, electrostatic attraction (outer-sphere complexation) and ligand exchange (inner-sphere complexation); *surface precipitation*; and *shape complementarity and pore filling by diffusion* (Bacelo et al., 2020; Loganathan et al., 2014; Wu, Wan, Zhang, Pan, & Lo, 2020; Yang et al., 2020).

Adsorption performance alongside corresponding P-removal mechanisms for several low-cost adsorbents (reported in the literature) are listed in Table 1 (an important factor in creating this Table was consideration of their applicability in real wastewater treatment systems). The two most utilised wastewater streams for P recovery noted were various agricultural waste effluents and secondary treated municipal wastewater (STWW). For example, He et al. (2017) achieved high P recovery from biogas slurry, with 220 mg of P recovered per g of adsorbent used (220 mg P/g), as a maximum adsorption capacity onto Fe-doped biochar made from corn straw. The biochar interacted with $H_2PO_4^-$, HPO_4^{2-} and PO_4^{3-} mainly through the formation of inner-sphere complexes within the coordination sphere of Fe(III). Moreover, a large number of hydroxyl groups encouraged surface reactions with P through hydrogen-bonding. Zheng et al. (2019) used STWW in batch and column adsorption experiments and results showed that an engineered biochar effectively removed P (8.34 mg P/L) with relatively fast kinetics (4 h), mainly through formation of outer-sphere complexes with positively charged functional groups. Successful adsorption of P was also achieved onto biochar (using an acid-extract from incinerated sewage sludge) which was mainly due to Ca-P and Mg-P precipitation (Fang et al., 2020). Liu et al. (2020) investigated a Mg-laden biochar (obtained from wood waste), to recover P from hydrolysed urine which was controlled by surface interactions and precipitation processes. Table 1 also highlights the diversity in precursor selection for adsorbent synthesis. Despite a now growing body of literature on P adsorption and recovery, many of these low-cost adsorbents would still benefit from further development and improvement (i.e., to achieve higher P selectivity). Work is also needed to ensure their environmental safety/low-toxicity (i.e., if they were to be re-used as fertilisers), to quantify P availability/desorption (from the saturated adsorbent), and to assess their practical efficacy (from a cost analysis perspective).

Table 1

Phosphorus adsorption capacities, wastewater effluents used, and governing adsorption mechanism reported in the literature using various biochars and different organic/inorganic waste/by-products.

Adsorbent	**Adsorption capacity (mg P/g)**	**Wastewater type**	**Adsorption mechanisms**	**Reference**
Biochar from crab shell	11.59	Biogas effluent of swine manure	Ca-P precipitation	(L. Dai et al., 2017)
Biochar from corn straw	220	Biogas slurry water	Inner-sphere complexes through Fe Hydrogen bonding	(He et al., 2017)
Biochars from wood, corncobs, rice husks and sawdust	5.41 - 7.67	Anaerobically digested liquid swine manure	Electrostatically attracted outer-sphere complexes Inner-sphere complexes with cations such as Ca, Mg, Al and Fe	(Kizito, Luo, et al., 2017)
Calcined waste eggshell	10.5	Leached solution form dewatered sludge	Ca-P precipitation	(Panagiotou et al., 2018)
Calcined waste eggshell	22.3	Real wastewater effluent	Ca-P precipitation	(Oliveira et al., 2015)
Thermally treated gastropod shell	3	Aquaculture wastewater	Formation of outer-sphere complexes Ca-P precipitation	(Oladoja, Adelagun, Ahmad, & Ololade, 2015)

Zirconium-loaded soybean residue (okara)	16.43	Real municipal wastewater	Inner-sphere complexes through Zr	(Nguyen et al., 2015)
Ground water treatment plant sludge	41.67	Secondary wastewater	Inner-sphere complexes through Fe and Al Formation of outer-sphere complexes	(Bal Krishna, Aryal, & Jansen, 2016)
Biochar from iron-rich sludge	1.84	Liquid phase of anaerobic digestate	Inner-sphere complexes through Fe Formation of outer-sphere complexes	(H. Wang et al., 2020)
Biochar from hickory wood chips	8.34	Secondary treated municipal wastewater	Formation of outer-sphere complexes	(Zheng et al., 2019)
Fe(III)-doped chitosan	10.2	Secondary treated municipal wastewater	Inner-sphere complexes through Fe Formation of outer-sphere complexes	(B. Zhang, Chen, Feng, & Zhang, 2018)
Black liquor-derived calcium-activated biochar	n.a.	Real wastewater effluent	Ca-P precipitation Inner-sphere complexes with cations	(X. Liu, Shen, Smith, & Qi, 2019)
Biochars from wood waste	180	Hydrolysed urine	Mg-P precipitation	(J. Liu et al., 2020)
Mg/Ca modified biochars from peanut shells	129.79	Acid-extract of incinerated sewage sludge ash	Ca-P and Mg-P precipitation	(L. Fang et al., 2020)
Low-temperature activated crab carapace	21.56	Secondary treated municipal wastewater	Inner- and outer-sphere complexation Ca–P precipitation	(Pap, Kirk, Bremner, Sekulic, et al., 2020)
Ferric oxide hydrate/biochar composite	51.71–56.15	Swine manure	Inner-sphere complexes through Fe Hydrogen bonding	(T. Zhang et al., 2018)

La-doped biochars derived from lignocellulosic wastes	36.06	Secondary treated municipal wastewater	Inner-sphere complexes through La Formation of outer-sphere complexes	(Q. Xu et al., 2019)
Biochar from microwave pyrolysis of rice husk	0.071	Secondary treated municipal wastewater	Hydrogen bonding	(Shukla, Sahoo, & Remya, 2019)
Chinese medicinal herbal residue and spent *Pleurotus ostreatus* substrate	63.41	Swine wastewater	Inner-sphere complexes Formation of outer-sphere complexes Precipitation	(Feng et al., 2020)
Bauxite residue	0.27	Two agricultural waters of low (forest run-off) and high (dairy soiled water) P content	Inner-sphere complexes through Fe and Al Formation of outer-sphere complexes	(Cusack et al., 2019)
Thermally treated seagrass residues	30.21	Supernatant of anaerobic digester and the liquid extracted from anaerobic dewatered sludge	Inner-sphere complexation Precipitation	(Photiou, Koutsokeras, & Constantinides, 2021)
Sun coral powder	9.59	Secondary treated municipal wastewater	Ca-P precipitation	(Vianna, Marques, & Bertolino, 2016)
Mg modified corn biochar	239	Swine wastewater	Mg-P precipitation	(C. Fang, Zhang, Li, Jiang, & Wang, 2014)
La modified platanus ball fiber biochar	148.11	Real wastewater effluent	Inner-sphere complexes through La Formation of outer-sphere complexes	(Jia, Zeng, Xu, Li, & Peng, 2020)

Desorption from saturated adsorbents and P plant availability

Whilst strong interactions and high affinities for P are vital for P adsorption from wastewater, they may not be ideal for subsequent fertiliser re-use. To assess the elution of P from saturated adsorbents (and soil-P bioavailability) there are many potential test methods available - but no clear consensus on the 'optimal assessment method'. In part, this reflects the large number of variables which can influence plant availability of P in different soils (Shepherd, Sohi, et al., 2016). P uptake by plants depends not only on P speciation, fractionation, and soil/adsorbent P level, but also on whether plant roots can efficiently uptake available P.

A review of different P desorption and P bioavailability methods that have been applied to various low-cost adsorbents is given in Table 2.

Table 2

Desorption and plant availability studies regarding adsorbed P - using biochars and different waste by-products.

Adsorbent	Desorption/release solution	P plant availability	Reference
Biochar from waste feedstocks	pH 7 MOPS-buffered deionised (DI) water for 4 days	n/a	(Shepherd, Sohi, et al., 2016)
Biochar from corn straw	DI water, citric acid at pH 4.8, and NaOH at pH 8.8 for 24 h	n/a	(He et al., 2017)
Biochars from sugarcane harvest residue	0.01 M NaCl, Na_2CO_3 and HCl for 4 days	Soil (type not defined) with 1% by wt. application rate *Ryegrass* planted for 21 days	(R. Li et al., 2016)
Biochar from tomato leaves	Mehlich 3 method and DI water	Seeds germination assay of grass seeds (first 13 days)	(Yao, Gao, Chen, & Yang, 2013)

Mussel shell	Phosphate fractionation	n/a	(Paradelo et al., 2016)
Biochar from roots of Undaria pinnatifid	n/a	Regular soil with 5% by volume application rate Lettuce planted for 21-30 days	(Jung, Kim, Jeong, & Ahn, 2016)
Biochar from iron-rich sludge	0.25 M NaOH for 6 h	Seed germination assay of grass seeds (first 10 days)	(H. Wang et al., 2020)
Biochar from water hyacinth plants	n/a	Maize (*Zea mays L.*) grown in sandy soil (Typic Torripsamment) 0.5% wt. application rate for 14 days	(Mosa, El-Ghamry, & Tolba, 2018)
Biochar from pre-treated cypress sawdust	DI water at pH 5.2, 7 and 9 for various times between 30 and 3600 min	n/a	(Haddad, Jellali, Jeguirim, Ben Hassen Trabelsi, & Limousy, 2018)
Cerium-modified biochar from straw	n/a	Soils from a rice field with 3%, w/w application rate Biochar effect on soil microbial metabolism	(H. Lu et al., 2019)
Biochar from cow dung	n/a	Seed germination assay of lettuce seeds (first 7 days)	(Chen, Qin, Sun, Cheng, & Shen, 2018)
Biochar from hickory wood chips	n/a	Seed germination assay of Mung bean (first 13 days)	(Zheng et al., 2019)
Biochar from food waste	n/a	Regular soil with 1% by wt. application rate Cabbage seed planted for 45 days	(Alghashm et al., 2018)
Biochar from farm residues	Phosphate fractionation and Olsen extraction	n/a	(Novais, Zenero,

			Tronto, Conz, & Cerri, 2018)
Biochar from iron-sludge	n/a	Seed germination assay of wheat seed (first 10 days)	(Xia et al., 2020)
Biochar from microalgae	n/a	Agricultural soil with 0.2 g/kg application rate Tomato plant planted for 30 days	(Arun, Gopinath, Vigneshwar, & Swetha, 2020)
Calcined sepiolite	Phosphate fractionation	Sandy loam soil with 0.5 g and 1.0 g/kg application rate Rice seeds planted for 35 days	(Hong, Ndingwan, Yoo, Lee, & Park, 2020)
Bentonite modified biochar	n/a	Regular soil with 0.2 g/kg application rate for 20 days	(X. An et al., 2020)
Concrete-waste	Calcium-acetate-lactate-extraction at pH 4 for 56 days	n/a	(dos Reis et al., 2020)
Mg-enriched biochar from manure and sludge	DI water, 2% citric acid and Mehlich-1 test for 4h	Oxisol (Rhodic Hapludox) with 200 mg/kg P application rate Seeds of maize planted for 21 days	(Nardis, Santana Da Silva Carneiro, Souza, Barros, & Azevedo Melo, 2020)

Some of the most widely used chemical extraction/desorption methods which seek to simulate ‘availability’ in soil environments are: the Olsen extraction, Mehlich-1 and 3 extraction, sequential extraction and extraction with different mineral acids (e.g., HNO_3, H_2SO_4, Aqua Regia) (H. Li, Li, Xu, & Lu, 2020). The Mehlich-1 test method was used by Yao et al. (2013) and Nardis et al. (2020) when looking at biochar. These studies both determined that ~19-20% of total P in post adsorption biochar was

Mehlich-1 extractable, however Mehlich-1 is an acid extractor and its capacity could be reduced in soils of high buffering capacity. Further, Novais et al. (2018) reported that the P released by the Olsen extraction (0.5 mol/L $NaHCO_3$ at pH 8.5) and distilled water from the biochar was much lower than with an acid based one (0.5 M H_2SO_4), which indicated poor P availability for plants in more alkali soils. Findings from these studies suggest that P-doped biochars have a high potential to be used as fertiliser in highly weathered tropical soils (more acidic conditions) where the rich organic matrix is negatively charged and has limited capacity to adsorb P. Paradelo et al. (2016) and Jiang et al. (2017) used a P fractionation method (sequential extraction) to determine which forms of P were desorbed from saturated adsorbents (mussel shell and calcium-silicate composite), these were: (i) loosely bound-P (desorbed in 0.5 M $NaHCO_3$), (ii) alkali-soluble P (0.1 M NaOH), (iii) acidic-soluble P (0.5 M HCl), (iv) residual P (6 M HCl). In both studies, approximately 90% of adsorbed P was recovered by the third step (0.5 M HCl solution) which suggested that predominantly acid-soluble P was present. Another advantage of the materials with a high P content bonded in their structure (shells, carapace, certain biochars), is that in acidic environment part of the bounded P could become available. P release kinetics from pre-loaded biochar was also investigated by Haddad et al. (2018) using distilled water at different initial pH values for various contact times (between 30 and 3600 min). Results showed that the release of P was clearly a time dependent process. Additionally, in continuous desorption experiments, He et al. (2017) revealed that the P release rate from saturated biochar was relatively slow , which points to it's potential as *slow release* fertiliser (which may well be of benefit in certain scenarios).

Rather than solely relying on desorption experiments, some studies have utilised seed germination assays and pot trials to gain further information about P plant availability from saturated adsorbents. Pot trials are clearly more realistic in terms of determining P availability and solubility in soil – however, results may vary markedly, depending on the plant species and soil type used (and as such, widely accepted ‘standardised’ methodologies are likely still required). In a study conducted by Zheng et al. (2019), quartz sand with un-laden biochar and P-laden biochar were used as growth media for a mung bean seedling growth study. The experiment showed that P-laden biochar increased seed germination rates from 30% (sand alone) to 46.7% (sand with P-laden biochar) – indicating that P-laden biochar (created in fixed-bed column through real wastewater filtration) could be used as a plant fertiliser to improve soil fertility. An interesting approach was also used by Xia et al. (2020)~~,~~ who pyrolysed P-laden alkali-treated iron sludge and successfully used this to support wheat growth. Cultivation experiments consisted of an experimental group (with biochar addition at a 10% by wt. application rate and two control groups (without biochar addition). The growth of the wheat dosed with biochar was noticeable in comparison to the control groups, where P was limited, and stagnant growth was observed. The work demonstrated possible P recovery potential within the WWTP chain, where not only the produced sludge was reused, but circulation of surplus P was also achieved. During pot trials conducted by Li et al. (2016), use of a P-loaded biochar also resulted in much greater plant growth height when compared to controls (without any supplement). Above-ground biomass for the P-loaded biochar treatment was 1.124 g/pot (dry weight of ryegrass), which was significantly larger than for controls (0.367 g/pot). Jung et al. (2016) further showed that for 21 day pot trials, plant growth rate was faster (with a larger overall plant yield) in soil mixed with biochar. The limitation of these studies is the lack of more detailed research on long term field application including the changes in soil chemical properties, soil microbial activity, and population dynamics with different soil types.

More broadly, the influence and benefit of biochar (or other P-enriched secondary materials) on soil P availability is still a somewhat debated issue. Commonly, increased soil P availability is documented in acidic soils, however, biochar can instead reduce P availability in neutral and alkaline soils due to P fixation/ binding (H. Lu et al., 2019). Ultimately, the net effect of P-enriched secondary materials on P availability in soil-plant systems will depend on a complex equation based on multiple sorption mechanisms that are at play - within the soil and the sorbent particles, alongside differences due to soil type, plant species and root uptake efficiency (among other factors) (M. Xu et al., 2019).

Scale-up approaches (pilot tests), cost viability and legislative perspectives

Efforts to upscale P recovery processes using adsorption in pilot-scale applications, with fixed-bed columns and with real wastewaters are increasingly occurring. Full scale-up of adsorbent production and P-removal is however still in its infancy – and there is still some way to go before such processes are widely embedded (i.e., in WWTW's). In support of this, Benafqir et al. (2019) undertook a Process Capability Study (CPS) which quantified the ability of a process to perform a task with desired characteristics within well-defined tolerances. The CPS indicated that an adsorption process with hematite–titaniferous sand adsorbent was capable and stable under large-scale applications; however, limitation of CPS still exists for large-scale data. Further, Shepherd et al. (2016b) used bench-scale experimental data and simple scale-up calculations to estimate adsorber dimensions for a larger WWTP application. They additionally estimated the agricultural surface area (ha) it would be possible to fertilise with the produced P enriched material (created at the WWTP). In these estimates, a large WWTP (PE > 50000) would produce enough P enriched material each year to fertilise >3200 ha of soil with ‘Index 0’ (a descriptive scale used for different nutrient concentrations and crop response in soil – lower the index number, lower the soil quality). Given similarities in different fixed-bed (column) process parameters such as empty bed contact time (EBCT), mass transfer zone (MTZ) and hydrodynamic characteristics between lab-scale and either pilot or full-scale systems, Jung et al. (2017) and Pap et al. (2020a) also calculated the parameters for, and simulated the performance of, a pilot-scale column system for P removal using the scale-up approach described by Worch (2012). The methodology showed good consistence in data between bench- and pilot-scale. However this mathematical tool does not allow a deeper insight into the mechanisms of the adsorption process because equilibrium relationships and kinetics are only indirectly considered, therefore only applicable under restrictive conditions, such as specific similarity criteria (Worch, 2012). Ezzati et al. (2020) used a rapid small-scale column test approach to make scale-up predictions regarding P retention in large-scale filters, which may include considerable savings on: time and space required for constructing and operating the large columns; amount of influent (chemicals and water); procurement/synthesis of the adsorbent and cost of laboratory analysis of water samples. The developed model successfully described the pattern of large-scale column performance, but further model validation is required for more accurate results. An et al. (2019) took forward laboratory column experiments and theoretical scale-up values to field-scale testing using hybrid chitosan beads as adsorbents combined with dissolved air flotation process. The tests showed that the P concentration in treated effluent consistently satisfied national discharge standards (0.2 mg P/L) within the Republic of Korea. Okano et al. (2016) developed a mobile pilot-scale plant for *in-situ* examination and demonstration of P recovery from wastewater. The mobile pilot plant consisted of a

1000 L reactor, a self-made filtration system and ancillary equipment. Using this plant, they evaluated the ability of amorphous calcium silicate hydrates to recover P from anaerobic sludge digestion liquor. On average, approximately 80% of P was recovered (during a process involving 20 min mixing, 30 min settling, and 90 min of filtration). In order to achieve P recovery from secondary WWTP effluent, Kalaitzidou et al. (2016) investigated adsorption onto several low-cost and commercially available adsorbents at bench-scale. Based on these experiments, they then successfully constructed and operated a pilot-plant, utilising iron-manganese oxy-hydroxides (AquAsZero) identified as the ‘best’ adsorbent from the laboratory tests. The unit was successfully operated (for 6 adsorption-regeneration cycles) and the material recovered was considered promising as a fertiliser, due to its high P content (35.4 wt.%) and near zero content of other toxic metals. Bolton et al. (2019) developed a pilot-scale wetland to treat domestic wastewater where functionalised biochar was added to the wetland cells. During a 7-month study, the cells containing biochar consistently reduced P to lower levels (than in cells without biochar), with an average inlet P concentration of 15.5 mg/L falling to < 2 mg/L. Despite these studies, most work on P adsorption reports only on bench/lab scale experiments (mostly in batch mode), and full scale-up work is still scarce. This is leading to a degree of stagnation in this field – and this ‘gap’ now needs to be bridged. This can only be achieved through increased demonstration of applied large scale research, alongside more support for adsorbent commercialisation via collaboration with key water quality stakeholders, industrial partners and regulators.

From an economic perspective, P adsorption systems should be designed to attain maximum recovery from a liquid phase, with low implementation, integration and maintenance costs. In terms of production and operating costs – systems based on biochars and other low-cost adsorbents have yet to be adequately studied. The cost of any individual adsorbent reflects several factors, including the availability of the local biomass precursor, conditions required during pyrolysis/preparation, availability of reactor filters, processing requirements and lifetime issues (Vikrant et al., 2018). The production price of any low-cost adsorbent is also highly country specific. Costs will further depend on whether the absorbent material is itself a primary product (with value), or, simply a by-product of different processes (e.g., heat and electricity production) (Mohan, Sarswat, Ok, & Pittman, 2014). The costs involved in applying a saturated P-rich adsorbent to soil are additionally important (Mohan et al., 2015). Ahmed et al. (2016) undertook a detailed review of the economic feasibility of biochar use and concluded that this depended on a range of factors - from raw material price to the efficiency of the production technology used - and a detailed (pilot plant-based) cost equation was proposed. The unit cost ($/ton) for producing and applying biochars in North Western Europe includes the following factors: the annualised capital expenditure of pyrolysis facility ($/y); the total annual operating expenses of pyrolysis facility ($/y); the total annual cost of feedstock harvesting ($/y); the total annual cost of feedstock transport $/y); the total annual cost of biochar transport ($/y); the annual revenue from electricity generation ($/y); the annual biochar production (ton/y); the unit cost of biochar application ($/ton). Additional cost might be required if feedstocks require intensive cleaning.

According to a recent survey of biochar vendors by the International Biochar Initiative (IBI), global biochar prices range from $80/t to $1448/t (Y. Dai et al., 2020). Photiou et al. (2021) considered this from another angle, whereby they took the cost of collection and disposal (~€70-80/t) of adsorbent precursors (i.e., seagrass residue) and calculated the net profit (~€5-20/t) for a company that may switch this around to an investment in P adsorbent production. Ajmal et al. (2020) and Maroušek et al. (2020) further compared the economics of unmodified vs modified biochars. It was concluded that modified materials were likely more economical than unmodified ones. While modification increases production costs, operation costs reduced since much higher P recovery potential existed with modified biochars. Li et al. (2020) compared the economics of triple-superphosphate (TS) fertiliser and P-rich biochar. According to their study, the price of TSP was ~$2.88/kg, while the cost to create 1 kg of P-laden biochar using maize stalk and potassium dihydrogen phosphate (KH_2PO_4) was comparable at ~$3.05/kg. Given that less P-laden biochar was needed (than TSP) to maintain soil P levels, they concluded that P-laden biochar could efficiently act to reduce soil P fertilisation costs. This was in part because of the slow-release nature of P laden onto biochar as well as the more homogeneous P distribution that occurred under P-laden biochar treatments. Bashar et al. (2018) went one step further, and evaluated several emerging high performance P removal/recovery technologies: i.e., the Modified University of Cape Town process (H. Zhang, Wang, Xiao, Yang, & Zhang, 2009), Bardenpho process (Ashrafi, Mehrabani Zeinabad, Borghei, Torresi, & Muñoz Sierra, 2019), membrane bioreactors (H. Zhang et al., 2009), Integrated Fixed-Film Activated Sludge Systems with Enhanced Biological Phosphorus Removal (Bai, Zhang, Quan, & Chen, 2015), struvite recovery and tertiary reactive media filtration. Their results showed that the Modified University of Cape Town biological nutrient removal system (with tertiary reactive media filtration/adsorption) was one of the most cost effective configurations (at ~$97/kg of P removed). Desmidt et al. (2015) carried out an economic feasibility study regarding the integrated adsorption/precipitation (struvite) process. They concluded that the largest operational cost for struvite precipitation related to the addition of a chemical Mg/Ca source. Therefore, the cost-benefit of P recovery could be significantly improved if waste from a Mg/Ca industry (or an Mg/Ca rich adsorbent) could be used as a source.

In terms of P levels in the environment – and specifically in freshwater receiving P rich discharges – there is no universal consensus on the concentration of P required to entirely prevent eutrophication, although most studies consider a concentration > 0.1 mg P/L to be too high (Suresh Kumar et al., 2019). The United States Environmental Protection Agency (USEPA) suggests a mean total P concentration of 0.01 mg P/L in its nutrient criteria guidelines for lakes and reservoirs (Rahman, Eckelman, Onnis-Hayden, & Gu, 2016). USEPA discharge permit limits can typically vary between 0.1 mg P/L up to 2 mg P/L in different states and depending on the sensitivity of the receiving water body. In the European Union (EU), standards for water quality are set by the Water Framework Directive (WFD), and the permissible P discharge value from 1 to 0.1 mg P/L was recently tightened (Kong et al., 2019). It must be noted that these effluent values serve as a guideline, since the risk posed by P discharged into the environment will not only depend on effluent concentration but also on the size/sensitivity of the receiving water body. Effluent regulations in individual EU member states tend to be 1 - 2 mg P/L, often depending on the population served by a WWTP (population equivalence), with more stringent values set in more sensitive areas (Suresh Kumar et al., 2019). China has municipal wastewater discharge limits ranging from 0.5 to 1 mg P/L (W. W. Li, Sheng, Zeng, Liu, & Yu, 2012).

Beyond P removal, wastewater discharge operations that recover P also need to consider market regulations, alongside health and environment protection laws. Often, lengthy authorisation processes to install systems (e.g., environmental impact assessment) and then recover P are required. Legislative harmonisation, which encompasses the inclusion of recycled P into existing fertiliser regulations, and supports new operators in this field, would speed up market penetration of novel technologies, reduce P losses and safeguard European quality standards (L. Egle, Rechberger, Krampe, & Zessner, 2016). Hukari et al. (2016) summarised the EU-legislation governing P recovery processes and market entry. These laws can be divided into three sections: (i) governing recovery and recycling operations, (ii) material type and (iii) market placement. Rules regarding the use of fertilisers were partially harmonised by European Commission (EC) Regulation No 2003/2003, which covers (almost exclusively), inorganic material–based fertilisers, extracted from mines or chemically produced (Hidalgo, Corona, & Martín-Marroquín, 2020). However, following Circular Economy Package (CEP) principles, the new EU Fertilising Products Regulations (EC No 2019/1009) aim to boost large-scale production of fertiliser from domestic organic or secondary raw materials. It also seeks to harmonise conditions to make fertilisers made from recycled or organic materials more available throughout the internal market (Nedelciu, Ragnarsdóttir, & Stjernquist, 2019). At the same time, EU-wide limits on contaminants (i.e., heavy metals and organic pollutants) in fertilisers/secondary products will be imposed (Verbeeck, Salaets, & Smolders, 2020). Further, in 2016, the EC nominated the STRUBIAS (STRUvite, BIochar, AShes) group to determine how recycled P fertilisers should become accepted for the fertiliser market in the EU. The group recently published its final report and various criteria are now expected to be adopted in the first quarter of 2021, which would be before the date of entry into application of the new EU Fertilising Products Regulations (Chojnacka, Moustakas, & Witek-Krowiak, 2020).

Case studies regarding integrated-hybrid P removal systems

Options to recover P occur at multiple points within WWTPs, however, the complexity of recovery and removal sometimes requires an integrated approach - whereby different technologies are combined to attain much higher efficiency. Egle et al. (2015) and Bunce et al. (2018) gave compressive overviews and descriptions of available technologies for removing/recovering P from municipal wastewater liquid and solid phases. About 50 technologies were identified at various levels of development (be that industrial-, full-, pilot- or laboratory-scale). But relatively few integrated P recovery technologies involved low-cost adsorbents (see Table 3).

Table 3

Integrated-hybrid P removal systems that have used biochars or different waste/by-products and metal-oxides/hydroxides.

Adsorbent	**Integrated-hybrid P system description**	**Reference**
Commercial activated carbon	Combination of GAC adsorption and deep-bed filtration with coagulation	(Altmann, Rehfeld, Träder, Sperlich, & Jekel, 2016)
Hydrous ferric oxide coated sand	Modified University of Cape Town biological nutrient removal with tertiary reactive media filtration/adsorption	(Bashar et al., 2018)
Chitosan beads	Adsorber containing chitosan beads following coagulation and DAF processes	(B. An et al., 2019)
Calcium salt	Hybrid precipitation–microfiltration process	(N. C. Lu & Liu, 2010)
Zirconium sulphate surfactant micelle mesostructure	Ultrafiltration membrane (polysulfone) embedded with zirconium sulphate for adsorption	(Furuya et al., 2017)
Iron oxide/hydroxide-based agglomerated adsorbent	Hybrid adsorption–ultrafiltration process	(Zelmanov & Semiat, 2014)
Metal oxide coated beads	Membrane bioreactor filtration and adsorption	(Park, Kwak, Mahardika, Mameda, & Choo, 2017)
Metal-Zr hydroxide	Membrane bioreactor filtration and adsorption	(Johir et al., 2016)

Steel slag	Biologically and chemically mediated simultaneous adsorption and precipitation	(Pratt, Parsons, Soares, & Martin, 2012)
Biochar	Algal based P recovery system with transformation of P-rich algae biomass to biochar	(Cole, Paul, de Nys, & Roberts, 2017)
Biochar	Biotransformation of P to biochar from enhanced biological phosphorus removal	(Qian, Lu, Soh, Webster, & Zhou, 2020; Qian, Wang, Le, & Zhou, 2019)
Biochar from corn cob and wood	Biochar-packed vertical flow constructed wetland columns	(Kizito, Lv, et al., 2017)
Biochar from bamboo	Electrolysis-integrated horizontal subsurface-flow constructed wetland amended with biochar	(Gao et al., 2018; Ju, Wu, Zhang, & Dong, 2014)
White hard clam shells	Horizontal sub-surface flow constructed wetland with adsorption	(Nguyen et al., 2020)
Biochar	Sand media amended with biochar in constructed wetland	(de Rozari, Greenway, & El Hanandeh, 2016)
Biochar from hemp enriched with iron	Iron enriched biochar substrate in constructed wetlands	(Bolton et al., 2019)

Altmann et al. (2016) investigated a combination of granular activated carbon (GAC) deep-bed filtration (GAC+sand), with coagulation, as an advanced treatment step for P removal from secondary effluent. GAC adsorption was also assessed as an upper filter layer in dual-media downflow filtration (sand) and as a mono-media for an up flow filter. Both filtration concepts effectively removed P, achieving effluent concentrations of 0.1 mg P/L. Bashar et al. (2018) considered six full-scale hybrid treatment scenarios. Each configuration consisted of preliminary and primary treatment, mainstream P removal, solid phase (sludge) line and biogas recovery from the sludge.

In one scenario (scenario 6), a reactive media filtration step (with continuous backwash, up-flow, and a deep-bed granular media filter) was integrated into the Modified University of Cape Town (MUCT) biological nutrient removal configuration (consisting of anaerobic, primary anoxic, secondary anoxic and aerobic processes) to reduce effluent P to 0.05 mg P/L. This configuration proved to be one of the most cost-effective scenarios, which also resulted in the lowest effluent P concentration. An et al. (2019) combined adsorption (onto chitosan beads) with coagulation and dissolved air flotation (DAF) processes. In pilot tests, the resultant P concentration did not always satisfy the desired regulation limit of 0.2 mg P/L (for Republic of Korea) with coagulation and DAF use only; however, the addition of adsorption consistently reduced effluent P to < 0.2 mg P/L. Several schematic diagrams (as examples) of integrated/hybrid P recovery processes are shown in Fig. 3.

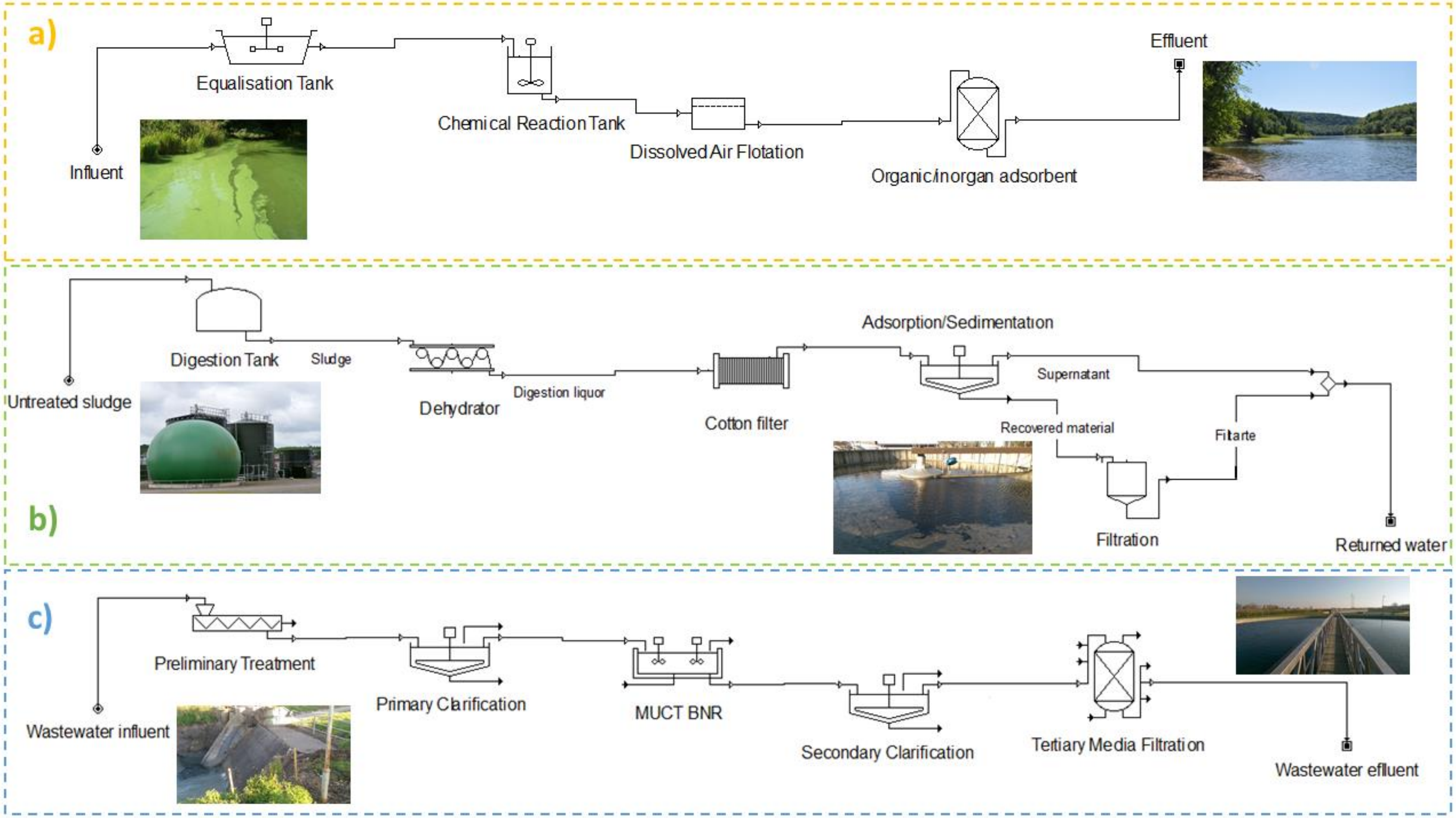

Fig. 3. Schematic diagrams showing integrated/hybrid P recovery processes: (a) organic/inorganic hybrid adsorbent integrated with dissolved air flotation (B. An et al., 2019), (b) sludge digestate treatment plant developed by (Okano et al., 2016) and (c) Modified University of Cape Towne (MUCT) biological nutrient removal (BNR) process with filtration media (Bashar et al., 2018).

Cole et al. (2017) used algal based P recovery (using the freshwater macroalga, *Oedogonium intermediu*) to recover P from municipal wastewater, then converted these cultivated algae into a soil ameliorant (a biochar). It has been shown that through this transformation the P held within the algae was stabilised, enabling it to be stored, transported and applied to agricultural land. A similar approach was utilised by Qian et al. (2020), where enhanced biological P removal sludge was used to produce a biochar as a potential P fertiliser. A low-temperature-steam activation method was developed to increase P availability in the biochar. This study also observed that different environmental conditions, i.e., environmental pH, ionic strength of the soil porewater and the presence of low-molecular-weight acids, had only minor or negligible effects on P-release from the biochar (Qian et al., 2019).

Integration of different low-cost adsorbents into constructed wetland structures is another promising approach for efficient P recovery. Kizito et al. (2017b) investigated three types of vertical flow constructed wetland columns, packed with corn cob biochar, wood biochar or gravel to recover P from anaerobic digested effluent. The biochar-packed wetland columns provided significantly higher removal of P (compared to gravel-packed columns). Better removal was explained by the larger surface area and higher porosity of the biochar, which enabled higher P adsorption and higher microbial colonisation rates. In the work by Gao et al. (2018), a pilot study using an electrolysis-integrated, biochar-amended, horizontal, subsurface-flow, constructed wetland was conducted. The electrolysis combined biochar substrate greatly enhanced P removal rates through the in-situ formation of ferric ions from a sacrificial iron anode which caused P chemical sedimentation and physical adsorption onto the iron modified biochar. Significant microbial diversity within biofilms that formed on the biochar substrate were also observed.

Park et al. (2017) combined membrane bioreactor filtration with adsorption. They fabricated mixed metal oxide coated beads from sulfonated polymer and tested these for P removal from membrane bioreactor effluents. The doping with metal oxides substantially enhanced adsorption rates and capacity, possibly due to increasing positively charged surfaces. After adsorption, the regenerated beads also showed higher P recovery performance than when originally used. Similar membrane adsorption hybrid systems were evaluated by Johir et al. (2016) for the removal of P from a high rate membrane bioreactor effluent. Due to low P removal by membranes, two adsorbents (an anion exchange resin and a metal-Zr hydroxide) were used for further P removal from effluent. It was found that the metal-Zr hydroxide enabled the elimination of > 85% of P from the effluent.

Conclusions, research gaps and future perspectives

At present, a wide variety of low-cost adsorbents have been successfully applied (at a variety of scales) to the removal and recovery of P from wastewater liquid phases, generally offering high removal efficiencies and capacities. Typical materials that are used include biochars (from different plant derivatives), calcium- and magnesium-based materials, and agricultural and industrial by-products. These will no-doubt continue to be used as adsorbents because of the advantages they can bring, i.e., being low cost materials, which host a diversity of physico-chemical removal mechanisms, with the additional capacity to be re-utilised as P enriched (adsorbent based) fertilisers. In exploiting these advantages, the principals of a more circular economy can be further embedded in future society. Furthermore, nanotechnology development is now offering new horizons for P removal and recovery. This is opening up new possibilities to prepare novel, highly tuned and cheap functionalised materials.

Adsorbent surfaces with selected metal nanoparticles (e.g., biochars coated with oxides and hydroxides of Fe, Zr, La, etc.), could offer high P adsorption capacities alongside high P selectivity – and in turn, help recovered P materials meet future quality and regulatory standards worldwide. However, environmental and biological impacts on soil and plants (and potential accumulation within food chains) remains to be fully investigated.

As the field of P recovery/removal from wastewater through adsorption is a ‘young’ research area, the progress is very dynamic, therefore, a few critical issues need to be addressed. As an essential precondition, selection of raw materials with appropriate compositions and the optimisation of biochars and other adsorbents fabrication conditions should be improved, as well as activation parameters with desirable properties for P recovery. In addition, a detailed development of design parameters with ‘smart’ adsorbent functionalisation would make the product highly efficient for target applications (e.g. selective P adsorption, future fertiliser product, etc). Extended research should be carried out on adsorption mechanisms involved during P adsorption to facilitate the development of effective methods for producing materials and optimising their efficiency for practical applications (particularly to meet strict P regulation requirements).

Overall, very few studies have actually been carried out in a fully integrated manner, i.e., to assess the feasibility of full scale implementation (of the tested low-cost adsorbents); their true potential for integration with other P recovery technologies; plant P-availability (if to be used as fertiliser); the chemical/microbiological ‘quality’ of the saturated adsorbent/product (i.e., as a soil amendment and fertiliser); and the environmental, logistical and economic considerations (through life-cycle assessments and cost-benefit analysis) of transitioning new products into the market economy.

Fig. 4 shows an overview of the steps and considerations needed to move from ‘raw material’ to a viable agricultural solution.

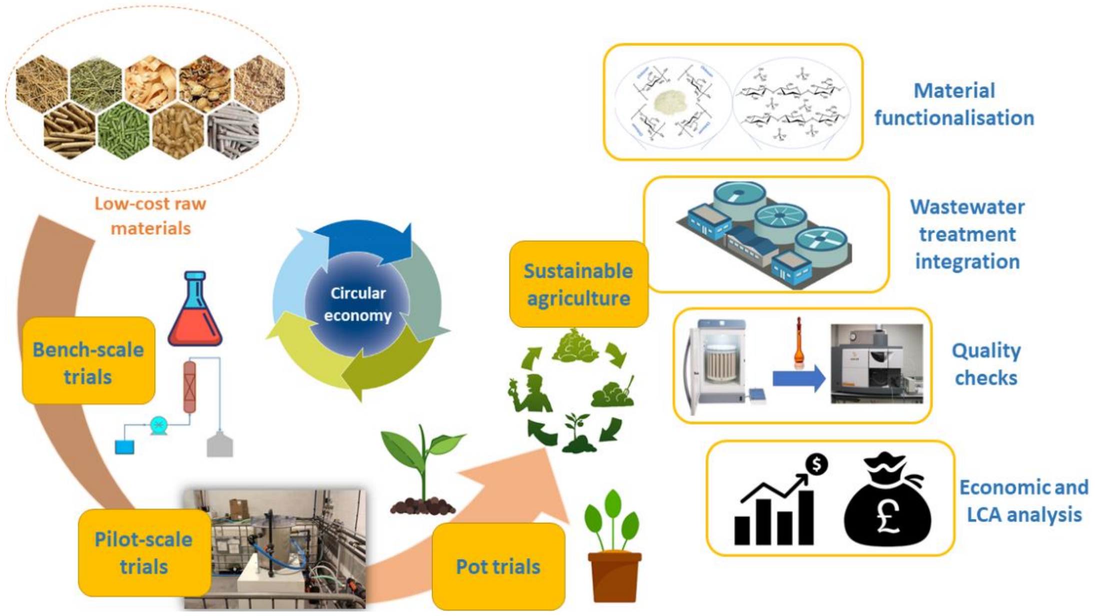

Fig. 4. Integrated P recovery - from raw material, through to P recovery from wastewater, through to sustainable agricultural re-use

There will never be a ‘one size fits all’ technology that works in all situations, however, the recent ‘resource demand’ triggered by impending P-rock scarcity is set to drive P recovery technology using low-cost adsorbents. In turn, this is also set to establish a more integrated and circular economy with regard to P management, and open up many new opportunities to fully and sustainably exploit finite P resources.

Acknowledgment

This work was undertaken as part of the ‘*Phos4You*’ Project (NWE 292) with financial support from the INTERREG V B Northwest Europe Programme.

References

Ahmed, M. B., Zhou, J. L., Ngo, H. H., & Guo, W. (2016). Insight into biochar properties and its cost analysis. *Biomass and Bioenergy*, 84, 76–86. Retrieved from https://doi.org/10.1016/j.biombioe.2015.11.002

Ajmal, Z., Muhmood, A., Dong, R., & Wu, S. (2020). Probing the efficiency of magnetically modified biomass-derived biochar for effective phosphate removal. *Journal of Environmental Management*, 253(August 2019), 109730. Retrieved from https://doi.org/10.1016/j.jenvman.2019.109730

Alghashm, S., Qian, S., Hua, Y., Wu, J., Zhang, H., Chen, W., & Shen, G. (2018). Properties of biochar from anaerobically digested food waste and its potential use in phosphorus recovery and soil amendment. *Sustainability (Switzerland)*, 10(12). Retrieved from https://doi.org/10.3390/su10124692

Altmann, J., Rehfeld, D., Träder, K., Sperlich, A., & Jekel, M. (2016). Combination of granular activated carbon adsorption and deep-bed filtration as a single advanced wastewater treatment step for organic micropollutant and phosphorus removal. *Water Research*, 92, 131–139. Retrieved from https://doi.org/10.1016/j.watres.2016.01.051

An, B., Lee, S., Kim, H. G., Zhao, D., Park, J. A., & Choi, J. W. (2019). Organic/inorganic hybrid adsorbent for efficient phosphate removal from a reservoir affected by algae bloom. *Journal of Industrial and Engineering Chemistry*, 69, 211–216. Retrieved from https://doi.org/10.1016/j.jiec.2018.09.029

An, X., Wu, Z., Yu, J., Ge, L., Li, T., Liu, X., & Yu, B. (2020). High-Efficiency Reclaiming Phosphate from an Aqueous Solution by Bentonite Modified Biochars: A Slow Release Fertilizer with a Precise Rate Regulation. *ACS Sustainable Chemistry and Engineering*, 8(15), 6090–6099. Retrieved from https://doi.org/10.1021/acssuschemeng.0c01112

Arun, J., Gopinath, K. P., Vigneshwar, S. S., & Swetha, A. (2020). Sustainable and eco-friendly approach for phosphorus recovery from wastewater by hydrothermally carbonized microalgae: Study on spent bio-char as fertilizer. *Journal of Water Process Engineering*, 38(July), 101567. Retrieved from https://doi.org/10.1016/j.jwpe.2020.101567

Ashrafi, E., Mehrabani Zeinabad, A., Borghei, S. M., Torresi, E., & Muñoz Sierra, J. (2019). Optimising nutrient removal of a hybrid five-stage Bardenpho and moving bed biofilm reactor process using response surface methodology. *Journal of Environmental Chemical Engineering*, 7(1). Retrieved from https://doi.org/10.1016/j.jece.2018.102861

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. *Chemical Engineering Journal*, 381(June 2019), 122566. Retrieved from https://doi.org/10.1016/j.cej.2019.122566

Bai, Y., Zhang, Y., Quan, X., & Chen, S. (2015). Nutrient removal performance and microbial characteristics of a full-scale IFAS-EBPR process treating municipal wastewater. *Water Science and Technology*, 73(6), 1261–1268. Retrieved from https://doi.org/10.2166/wst.2015.604

Bal Krishna, K. C., Aryal, A., & Jansen, T. (2016). Comparative study of ground water treatment plants sludges to remove phosphorous from wastewater. *Journal of Environmental Management*, 180, 17–23. Retrieved from https://doi.org/10.1016/j.jenvman.2016.05.006

Bashar, R., Gungor, K., Karthikeyan, K. G., & Barak, P. (2018). Cost effectiveness of phosphorus removal processes in municipal wastewater treatment. *Chemosphere*, 197, 280–290. Retrieved from https://doi.org/10.1016/j.chemosphere.2017.12.169

Benafqir, M., Anfar, Z., Abbaz, M., El Haouti, R., Lhanafi, S., Azougarh, Y., … El Alem, N. (2019). Hematite–titaniferous sand as a new low-cost adsorbent for orthophosphates removal: Adsorption, mechanism and Process Capability study. *Environmental Technology and Innovation*, 13, 153–165. Retrieved from https://doi.org/10.1016/j.eti.2018.10.009

Bhattacharjee, S., Darwish, N., & Shanableh, A. (2020). Phosphate removal using nanoscale zerovalent iron: Impact of chitosan and humic acid. *Journal of Environmental Chemical Engineering*, 8(5), 104131. Retrieved from https://doi.org/10.1016/j.jece.2020.104131

Bolton, L., Joseph, S., Greenway, M., Donne, S., Munroe, P., & Marjo, C. E. (2019). Phosphorus adsorption onto an enriched biochar substrate in constructed wetlands treating wastewater. *Ecological Engineering: X*, 1(June 2018), 100005. Retrieved from https://doi.org/10.1016/j.ecoena.2019.100005

Bunce, J. T., Ndam, E., Ofiteru, I. D., Moore, A., & Graham, D. W. (2018). A Review of Phosphorus Removal Technologies and Their Applicability to Small-Scale Domestic Wastewater Treatment Systems. *Frontiers in Environmental Science*, 6(8), 0–15. Retrieved from https://doi.org/10.3389/fenvs.2018.00008

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. *Journal of Cleaner Production*, 172, 2009–2018. Retrieved from https://doi.org/10.1016/j.jclepro.2017.11.224

Chojnacka, K., Moustakas, K., & Witek-Krowiak, A. (2020). Bio-based fertilizers: A practical approach towards circular economy. *Bioresource Technology*, 295(September 2019), 122223. Retrieved from https://doi.org/10.1016/j.biortech.2019.122223

Chrispim, M. C., Scholz, M., & Nolasco, M. A. (2019). Phosphorus recovery from municipal wastewater treatment: Critical review of challenges and opportunities for developing countries. *Journal of Environmental Management*, 248(July), 109268. Retrieved from https://doi.org/10.1016/j.jenvman.2019.109268

Cole, A. J., Paul, N. A., de Nys, R., & Roberts, D. A. (2017). Good for sewage treatment and good for agriculture: Algal based compost and biochar. *Journal of Environmental Management*, 200, 105–113. Retrieved from https://doi.org/10.1016/j.jenvman.2017.05.082

Cusack, P. B., Callery, O., Courtney, R., Ujaczki, É., 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. *Journal of Environmental Management*, 241(April), 273–283. Retrieved from https://doi.org/10.1016/j.jenvman.2019.04.042

Dai, L., Tan, F., Li, H., Zhu, N., He, M., Zhu, Q., … Zhao, J. (2017). Calcium-rich biochar from the pyrolysis of crab shell for phosphorus removal. *Journal of Environmental Management*, 198, 70–74. Retrieved from https://doi.org/10.1016/j.jenvman.2017.04.057

Dai, Y., Wang, W., Lu, L., Yan, L., & Yu, D. (2020). Utilization of biochar for the removal of nitrogen and phosphorus. *Journal of Cleaner Production*, 257. Retrieved from https://doi.org/10.1016/j.jclepro.2020.120573

de Rozari, P., Greenway, M., & El Hanandeh, A. (2016). Phosphorus removal from secondary sewage and septage using sand media amended with biochar in constructed wetland mesocosms. *Science of the Total Environment*, 569–570, 123–133. Retrieved from https://doi.org/10.1016/j.scitotenv.2016.06.096

Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, L., Van Der Bruggen, B., Verstraete, W., … Meesschaert, B. (2015). Global phosphorus scarcity and full-scale P-recovery techniques: A review. *Critical Reviews in Environmental Science and Technology*, 45(4), 336–384. Retrieved from https://doi.org/10.1080/10643389.2013.866531

dos Reis, G. S., Thue, P. S., Cazacliu, B. G., Lima, E. C., Sampaio, C. H., Quattrone, M., … Dotto, G. L. (2020). Effect of concrete carbonation on phosphate removal through adsorption process and its potential application as fertilizer. *Journal of Cleaner Production*, 256, 120416. Retrieved from https://doi.org/10.1016/j.jclepro.2020.120416

Egle, L., Rechberger, H., Krampe, J., & Zessner, M. (2016). Phosphorus recovery from municipal wastewater: An integrated comparative technological, environmental and economic assessment of P recovery technologies. *Science of the Total Environment*, 571, 522–542. Retrieved from https://doi.org/10.1016/j.scitotenv.2016.07.019

Egle, Lukas, Rechberger, H., & Zessner, M. (2015). Overview and description of technologies for recovering phosphorus from municipal wastewater. *Resources, Conservation and Recycling*, 105, 325–346. Retrieved from https://doi.org/10.1016/j.resconrec.2015.09.016

Ehmann, A., Bach, I. M., Laopeamthong, S., Bilbao, J., & Lewandowski, I. (2017). Can phosphate salts recovered from manure replace conventional phosphate fertilizer? *Agriculture (Switzerland)*, 7(1). Retrieved from https://doi.org/10.3390/agriculture7010001

Ezzati, G., Healy, M. G., Christianson, L., Daly, K., Fenton, O., Feyereisen, G., … Callery, O. (2020). Use of rapid small-scale column tests for simultaneous prediction of phosphorus and nitrogen retention in large-scale filters. *Journal of Water Process Engineering*, 37(February), 101473. Retrieved from https://doi.org/10.1016/j.jwpe.2020.101473

Fang, C., Zhang, T., Li, P., Jiang, R. F., & Wang, Y. C. (2014). Application of magnesium modified corn biochar for phosphorus removal and recovery from swine wastewater. *International Journal of Environmental Research and Public Health*, 11(9), 9217–9237. Retrieved from https://doi.org/10.3390/ijerph110909217

Fang, L., Li, J. shan, Donatello, S., Cheeseman, C. R., Poon, C. S., & Tsang, D. C. W. (2020). Use of Mg/Ca modified biochars to take up phosphorus from acid-extract of incinerated sewage sludge ash (ISSA) for fertilizer application. *Journal of Cleaner Production*, 244, 118853. Retrieved from https://doi.org/10.1016/j.jclepro.2019.118853

Feng, C., Zhang, S., Wang, Y., Wang, G., Pan, X., Zhong, Q., … Yao, P. (2020). Synchronous removal of ammonium and phosphate from swine wastewater by two agricultural waste based adsorbents: Performance and mechanisms. *Bioresource Technology*, 307(March), 123231. Retrieved from https://doi.org/10.1016/j.biortech.2020.123231

Furuya, K., Hafuka, A., Kuroiwa, M., Satoh, H., Watanabe, Y., & Yamamura, H. (2017). Development of novel polysulfone membranes with embedded zirconium sulfate-surfactant micelle mesostructure for phosphate recovery from water through membrane filtration. *Water Research*, 124, 521–526. Retrieved from https://doi.org/10.1016/j.watres.2017.08.005

Gao, Y., Zhang, W., Gao, B., Jia, W., Miao, A., Xiao, L., & Yang, L. (2018). Highly efficient removal of nitrogen and phosphorus in an electrolysis-integrated horizontal subsurface-flow constructed wetland amended with biochar. *Water Research*, 139, 301–310. Retrieved from https://doi.org/10.1016/j.watres.2018.04.007

Haddad, K., Jellali, S., Jeguirim, M., Ben Hassen Trabelsi, A., & Limousy, L. (2018). Investigations on phosphorus recovery from aqueous solutions by biochars derived from magnesium-pretreated cypress sawdust. *Journal of Environmental Management*, 216, 305–314. Retrieved from https://doi.org/10.1016/j.jenvman.2017.06.020

He, X., Zhang, T., Ren, H., Li, G., Ding, L., & Pawlowski, L. (2017). Phosphorus recovery from biogas slurry by ultrasound/H2O2 digestion coupled with HFO/biochar adsorption process. *Waste Management*, 60, 219–229. Retrieved from https://doi.org/10.1016/j.wasman.2016.08.032

Hidalgo, D., Corona, F., & Martín-Marroquín, J. M. (2020). Nutrient recycling: from waste to crop. *Biomass Conversion and Biorefinery*, (4). Retrieved from https://doi.org/10.1007/s13399-019-00590-3

Hong, S. H., Ndingwan, A. M., Yoo, S. C., Lee, C. G., & Park, S. J. (2020). Use of calcined sepiolite in removing phosphate from water and returning phosphate to soil as phosphorus fertilizer. *Journal of Environmental Management*, 270(June), 110817. Retrieved from https://doi.org/10.1016/j.jenvman.2020.110817

Huang, W., Zhang, Y., & Li, D. (2017). Adsorptive removal of phosphate from water using mesoporous materials: A review. *Journal of Environmental Management*, 193, 470–482. Retrieved from https://doi.org/10.1016/j.jenvman.2017.02.030

Hukari, S., Hermann, L., & Nättorp, A. (2016). From wastewater to fertilisers - Technical overview and critical review of European legislation governing phosphorus recycling. *Science of the Total Environment*, 542, 1127–1135. Retrieved from https://doi.org/10.1016/j.scitotenv.2015.09.064

Jia, Z., Zeng, W., Xu, H., Li, S., & Peng, Y. (2020). Adsorption removal and reuse of phosphate from wastewater using a novel adsorbent of lanthanum-modified platanus biochar. *Process Safety and Environmental Protection*, 140, 221–232. Retrieved from https://doi.org/10.1016/j.psep.2020.05.017

Jiang, D., Amano, Y., & Machida, M. (2017). Removal and recovery of phosphate from water by a magnetic Fe3O4 @ASC adsorbent. *Journal of Environmental Chemical Engineering*, 5(5), 4229–4238. Retrieved from https://doi.org/10.1016/j.jece.2017.08.007

Johir, M. A. H., Nguyen, T. T., Mahatheva, K., Pradhan, M., Ngo, H. H., Guo, W., & Vigneswaran, S. (2016). Removal of phosphorus by a high rate membrane adsorption hybrid system. *Bioresource Technology*, 201, 365–369. Retrieved from https://doi.org/10.1016/j.biortech.2015.11.045

Ju, X., Wu, S., Zhang, Y., & Dong, R. (2014). Intensified nitrogen and phosphorus removal in a novel electrolysis-integrated tidal flow constructed wetland system. *Water Research*, 59, 37–45. Retrieved from https://doi.org/10.1016/j.watres.2014.04.004

Jung, K. W., Jeong, T. U., Choi, J. W., Ahn, K. H., & Lee, S. H. (2017). Adsorption of phosphate from aqueous solution using electrochemically modified biochar calcium-alginate beads: Batch and fixed-bed column performance. *Bioresource Technology*, 244(July), 23–32. Retrieved from https://doi.org/10.1016/j.biortech.2017.07.133

Jung, K. W., Kim, K., Jeong, T. U., & Ahn, K. H. (2016). Influence of pyrolysis temperature on characteristics and phosphate adsorption capability of biochar derived from waste-marine macroalgae (Undaria pinnatifida roots). *Bioresource Technology*, 200, 1024–1028. Retrieved from https://doi.org/10.1016/j.biortech.2015.10.016

Kalaitzidou, K., Mitrakas, M., Raptopoulou, C., Tolkou, A., Palasantza, P. A., & Zouboulis, A. (2016). Pilot-Scale Phosphate Recovery from Secondary Wastewater Effluents. *Environmental Processes*, 3, 5–22. Retrieved from https://doi.org/10.1007/s40710-016-0139-1

Kizito, S., Luo, H., Wu, S., Ajmal, Z., Lv, T., & Dong, R. (2017). Phosphate recovery from liquid fraction of anaerobic digestate using four slow pyrolyzed biochars: Dynamics of adsorption, desorption and regeneration. *Journal of Environmental Management*, 201, 260–267. Retrieved from https://doi.org/10.1016/j.jenvman.2017.06.057

Kizito, S., Lv, T., Wu, S., Ajmal, Z., Luo, H., & Dong, R. (2017). Treatment of anaerobic digested effluent in biochar-packed vertical flow constructed wetland columns: Role of media and tidal operation. *Science of the Total Environment*, 592, 197–205. Retrieved from https://doi.org/10.1016/j.scitotenv.2017.03.125

Kong, L., Tian, Y., Wang, Y., Li, N., Liu, Y., Pang, Z., … Zuo, W. (2019). Periclaseinduced generation of flowerlike clay-based layered double hydroxides: A highly efficient phosphate scavenger and solid-phase fertilizer. *Chemical Engineering Journal*, 359(October 2018), 902–913. Retrieved from https://doi.org/10.1016/j.cej.2018.11.007

Li, H., Li, Y., Xu, Y., & Lu, X. (2020). Biochar phosphorus fertilizer effects on soil phosphorus availability. *Chemosphere*, 244, 125471. Retrieved from https://doi.org/10.1016/j.chemosphere.2019.125471

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

Li, W. W., Sheng, G. P., Zeng, R. J., Liu, X. W., & Yu, H. Q. (2012). China’s wastewater discharge standards in urbanization: Evolution, challenges and implications: Evolution, challenges and implications. *Environmental Science and Pollution Research*, 19(5), 1422–1431. Retrieved from https://doi.org/10.1007/s11356-011-0572-7

Liu, J., Zheng, M., Wang, C., Liang, C., Shen, Z., & Xu, K. (2020). A green method for the simultaneous recovery of phosphate and potassium from hydrolyzed urine as value-added fertilizer using wood waste. *Resources, Conservation and Recycling*, 157(October 2019), 104793. Retrieved from https://doi.org/10.1016/j.resconrec.2020.104793

Liu, R., Chi, L., Wang, X., Sui, Y., Wang, Y., & Arandiyan, H. (2018). Review of metal (hydr)oxide and other adsorptive materials for phosphate removal from water. *Journal of Environmental Chemical Engineering*, 6(4), 5269–5286. Retrieved from https://doi.org/10.1016/j.jece.2018.08.008

Liu, X., Shen, F., Smith, R. L., & Qi, X. (2019). Black liquor-derived calcium-activated biochar for recovery of phosphate from aqueous solutions. *Bioresource Technology*, 294(38), 122198. Retrieved from https://doi.org/10.1016/j.biortech.2019.122198

Loganathan, P., Vigneswaran, S., Kandasamy, J., & Bolan, N. S. (2014). Removal and recovery of phosphate from water using sorption. *Critical Reviews in Environmental Science and Technology*, 44(8), 847–907. Retrieved from https://doi.org/10.1080/10643389.2012.741311

Lu, H., Feng, Y., Feng, Y., Dong, Y., Sun, H., Xing, J., … Yang, L. (2019). Cerium-modified biochar: A recycling biomaterial for regulating phosphorus availability in paddy ecosystem from coastal mudflat reclamation. *Geoderma*, 346(50), 43–51. Retrieved from https://doi.org/10.1016/j.geoderma.2019.03.025

Lu, N. C., & Liu, J. C. (2010). Removal of phosphate and fluoride from wastewater by a hybrid precipitation-microfiltration process. *Separation and Purification Technology*, 74(3), 329–335. Retrieved from https://doi.org/10.1016/j.seppur.2010.06.023

Maroušek, J., Kolář, L., Strunecký, O., Kopecký, M., Bartoš, P., Maroušková, A., … Vrbka, J. (2020). Modified biochars present an economic challenge to phosphate management in wastewater treatment plants. *Journal of Cleaner Production*, 272. Retrieved from https://doi.org/10.1016/j.jclepro.2020.123015

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. *Bioresource Technology*, 160, 191–202. Retrieved from https://doi.org/10.1016/j.biortech.2014.01.120

Mosa, A., El-Ghamry, A., & Tolba, M. (2018). Functionalized biochar derived from heavy metal rich feedstock: Phosphate recovery and reusing the exhausted biochar as an enriched soil amendment. *Chemosphere*, 198, 351–363. Retrieved from https://doi.org/10.1016/j.chemosphere.2018.01.113

Muisa, N., Nhapi, I., Ruziwa, W., & Manyuchi, M. M. (2020). Utilization of alum sludge as adsorbent for phosphorus removal in municipal wastewater: A review. *Journal of Water Process Engineering*, 35(February), 101187. Retrieved from https://doi.org/10.1016/j.jwpe.2020.101187

Nardis, B. O., Santana Da Silva Carneiro, J., Souza, I. M. G. De, Barros, R. G. De, & Azevedo Melo, L. C. (2020). Phosphorus recovery using magnesium-enriched biochar and its potential use as fertilizer. *Archives of Agronomy and Soil Science*, 00(00), 1–17. Retrieved from https://doi.org/10.1080/03650340.2020.1771699

Nedelciu, C. E., Ragnarsdóttir, K. V., & Stjernquist, I. (2019). From waste to resource: A systems dynamics and stakeholder analysis of phosphorus recycling from municipal wastewater in Europe. *Ambio*, 48(7), 741–751. Retrieved from https://doi.org/10.1007/s13280-018-1097-9

Nguyen, T. A. H., Ngo, H. H., Guo, W. S., Nguyen, T. H. H., Soda, S., Vu, N. D., … Pham, T. T. (2020). White hard clam (Meretrix lyrata) shells media to improve phosphorus removal in lab-scale horizontal sub-surface flow constructed wetlands: Performance, removal pathways, and lifespan. *Bioresource Technology*, 312(April). Retrieved from https://doi.org/10.1016/j.biortech.2020.123602

Nguyen, T. A. H., Ngo, H. H., Guo, W. S., Pham, T. Q., Li, F. M., Nguyen, T. V., & Bui, X. T. (2015). Adsorption of phosphate from aqueous solutions and sewage using zirconium loaded okara (ZLO): Fixed-bed column study. *Science of the Total Environment*, 523, 40–49. Retrieved from https://doi.org/10.1016/j.scitotenv.2015.03.126

Novais, S. V., Zenero, M. D. O., Tronto, J., Conz, R. F., & Cerri, C. E. P. (2018). Poultry manure and sugarcane straw biochars modified with MgCl2 for phosphorus adsorption. *Journal of Environmental Management*, 214, 36–44. Retrieved from https://doi.org/10.1016/j.jenvman.2018.02.088

Okano, K., Miyamaru, S., Yamamoto, Y., Kunisada, M., Takano, H., Toda, M., … Ohtake, H. (2016). A mobile pilot-scale plant for in situ demonstration of phosphorus recovery from wastewater using amorphous calcium silicate hydrates. *Separation and Purification Technology*, 170, 116–121. Retrieved from https://doi.org/10.1016/j.seppur.2016.06.040

Oladoja, N. A., Adelagun, R. O. A., Ahmad, A. L., & Ololade, I. A. (2015). Phosphorus recovery from aquaculture wastewater using thermally treated gastropod shell.

Process Safety and Environmental Protection, 98, 296–308. Retrieved from https://doi.org/10.1016/j.psep.2015.09.006

Oliveira, M., Araújo, A., Azevedo, G., Pereira, M. F. R., Neves, I. C., & Machado, A. V. (2015). Kinetic and equilibrium studies of phosphorous adsorption: Effect of physical and chemical properties of adsorption agent. *Ecological Engineering*, 82, 527–530. Retrieved from https://doi.org/10.1016/j.ecoleng.2015.05.020

Panagiotou, E., Kafa, N., Koutsokeras, L., Kouis, P., Nikolaou, P., Constantinides, G., & Vyrides, I. (2018). Turning calcined waste egg shells and wastewater to Brushite: Phosphorus adsorption from aqua media and anaerobic sludge leach water. *Journal of Cleaner Production*, 178, 419–428. Retrieved from https://doi.org/10.1016/j.jclepro.2018.01.014

Pap, S., Kirk, C., Bremner, B., Sekulic, M. T., Shearer, L., Gibb, S. W., & Taggart, M. A. (2020). Low-cost chitosan-calcite adsorbent development for potential phosphate removal and recovery from wastewater effluent. *Water Research*, 173, 115573. Retrieved from https://doi.org/10.1016/j.watres.2020.115573

Pap, S., Kirk, C., Bremner, B., Turk Sekulic, M., Gibb, S. W., Maletic, S., & Taggart, M. A. (2020). Synthesis optimisation and characterisation of chitosan-calcite adsorbent from fishery-food waste for phosphorus removal. *Environmental Science and Pollution Research*, 27(9), 9790–9802. Retrieved from https://doi.org/10.1007/s11356-019-07570-0

Paradelo, R., Conde-Cid, M., Cutillas-Barreiro, L., Arias-Estévez, M., Nóvoa-Muñoz, J. C., Álvarez-Rodríguez, E., … Núñez-Delgado, A. (2016). Phosphorus removal from wastewater using mussel shell: Investigation on retention mechanisms. *Ecological Engineering*, 97, 558–566. Retrieved from https://doi.org/10.1016/j.ecoleng.2016.10.066

Park, H. S., Kwak, S. H., Mahardika, D., Mameda, N., & Choo, K. H. (2017). Mixed metal oxide coated polymer beads for enhanced phosphorus removal from membrane bioreactor effluents. *Chemical Engineering Journal*, 319, 240–247. Retrieved from https://doi.org/10.1016/j.cej.2017.03.017

Photiou, P., Koutsokeras, L., & Constantinides, G. (2021). Phosphate removal from synthetic and real wastewater using thermally treated seagrass residues of Posidonia oceanica. *Journal of Cleaner Production*, 278, 123294. Retrieved from https://doi.org/10.1016/j.jclepro.2020.123294

Pratt, C., Parsons, S. A., Soares, A., & Martin, B. D. (2012). Biologically and chemically mediated adsorption and precipitation of phosphorus from wastewater. *Current Opinion in Biotechnology*, 23(6), 890–896. Retrieved from https://doi.org/10.1016/j.copbio.2012.07.003

Qian, T., Lu, D., Soh, Y. N. A., Webster, R. D., & Zhou, Y. (2020). Biotransformation of phosphorus in enhanced biological phosphorus removal sludge biochar. *Water Research*, 169, 115255. Retrieved from https://doi.org/10.1016/j.watres.2019.115255

Qian, T., Wang, L., Le, C., & Zhou, Y. (2019). Low-temperature-steam activation of phosphorus in biochar derived from enhanced biological phosphorus removal (EBPR) sludge. *Water Research*, 161, 202–210. Retrieved from https://doi.org/10.1016/j.watres.2019.06.008

Rahman, S. M., Eckelman, M. J., Onnis-Hayden, A., & Gu, A. Z. (2016). Life-Cycle Assessment of Advanced Nutrient Removal Technologies for Wastewater Treatment. *Environmental Science and Technology*, 50(6), 3020–3030. Retrieved from https://doi.org/10.1021/acs.est.5b05070

Schröder, J. J., Smit, A. L., Cordell, D., & Rosemarin, A. (2011). Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use. *Chemosphere*, 84(6), 822–831. Retrieved from https://doi.org/10.1016/j.chemosphere.2011.01.065

Shepherd, J. G., Kleemann, R., Bahri-Esfahani, J., Hudek, L., Suriyagoda, L., Vandamme, E., & van Dijk, K. C. (2016). The future of phosphorus in our hands. *Nutrient Cycling in Agroecosystems*, 104(3), 281–287. Retrieved from https://doi.org/10.1007/s10705-015-9742-1

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 Research*, 94, 155–165. Retrieved from https://doi.org/10.1016/j.watres.2016.02.038

Shukla, N., Sahoo, D., & Remya, N. (2019). Biochar from microwave pyrolysis of rice husk for tertiary wastewater treatment and soil nourishment. *Journal of Cleaner Production*, 235, 1073–1079. Retrieved from https://doi.org/10.1016/j.jclepro.2019.07.042

Solovchenko, A., Verschoor, A. M., Jablonowski, N. D., & Nedbal, L. (2016). Phosphorus from wastewater to crops: An alternative path involving microalgae. *Biotechnology Advances*, 34(5), 550–564. Retrieved from https://doi.org/10.1016/j.biotechadv.2016.01.002

Song, M., & Li, M. (2019). Adsorption and regeneration characteristics of phosphorus from sludge dewatering filtrate by magnetic anion exchange resin. *Environmental Science and Pollution Research*, 26(33), 34233–34247. Retrieved from https://doi.org/10.1007/s11356-018-4049-9

Suresh Kumar, P., Ejerssa, W. W., Wegener, C. C., Korving, L., Dugulan, A. I., Temmink, H., … Witkamp, G. J. (2018). Understanding and improving the reusability of phosphate adsorbents for wastewater effluent polishing. *Water Research*, 145, 365–374. Retrieved from https://doi.org/10.1016/j.watres.2018.08.040

Suresh Kumar, P., Korving, L., van Loosdrecht, M. C. M., & Witkamp, G. J. (2019). Adsorption as a technology to achieve ultra-low concentrations of phosphate: Research gaps and economic analysis. *Water Research X*, 4, 100029. Retrieved from https://doi.org/10.1016/j.wroa.2019.100029

Tan, Z., Lin, C. S. K., Ji, X., & Rainey, T. J. (2017). Returning biochar to fields: A review. *Applied Soil Ecology*, 116(March), 1–11. Retrieved from https://doi.org/10.1016/j.apsoil.2017.03.017

Verbeeck, M., Salaets, P., & Smolders, E. (2020). Trace element concentrations in mineral phosphate fertilizers used in Europe: A balanced survey. *Science of the Total Environment*, 712, 136419. Retrieved from https://doi.org/10.1016/j.scitotenv.2019.136419

Vianna, M. T. G., Marques, M., & Bertolino, L. C. (2016). Sun coral powder as adsorbent: Evaluation of phosphorus removal in synthetic and real wastewater. *Ecological Engineering*, 97, 13–22. Retrieved from https://doi.org/10.1016/j.ecoleng.2016.08.004

Vikrant, K., Kim, K. H., Ok, Y. S., Tsang, D. C. W., Tsang, Y. F., Giri, B. S., & Singh, R. S. (2018). Engineered/designer biochar for the removal of phosphate in water and wastewater. *Science of the Total Environment*, 616–617, 1242–1260. Retrieved from https://doi.org/10.1016/j.scitotenv.2017.10.193

Wang, H., Xiao, K., Yang, J., Yu, Z., Yu, W., Xu, Q., … Liu, B. (2020). Phosphorus recovery from the liquid phase of anaerobic digestate using biochar derived from iron−rich sludge: A potential phosphorus fertilizer. *Water Research*, 174. Retrieved from https://doi.org/10.1016/j.watres.2020.115629

Wang, L., Wang, J., He, C., Lyu, W., Zhang, W., Yan, W., & Yang, L. (2019). Development of rare earth element doped magnetic biochars with enhanced phosphate adsorption performance. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 561(November 2018), 236–243. Retrieved from https://doi.org/10.1016/j.colsurfa.2018.10.082

Worch, E. (2012). *Adsorption Technology in Water Treatment: Fundamentals, Processes, and Modeling*. De Gruyter. Retrieved from https://books.google.rs/books?id=xUBhp6r6zwwC

Wu, B., Wan, J., Zhang, Y., Pan, B., & Lo, I. M. C. (2020). Selective Phosphate Removal from Water and Wastewater using Sorption: Process Fundamentals and Removal Mechanisms. *Environmental Science and Technology*, (852). Retrieved from https://doi.org/10.1021/acs.est.9b05569

Xia, W. J., Xu, L. Z. J., Yu, L. Q., Zhang, Q., Zhao, Y. H., Xiong, J. R., … Jin, R. C. (2020). Conversion of municipal wastewater-derived waste to an adsorbent for phosphorus recovery from secondary effluent. *Science of the Total Environment*, 705, 135959. Retrieved from https://doi.org/10.1016/j.scitotenv.2019.135959

Xu, M., Gao, P., Yang, Z., Su, L., Wu, J., Yang, G., … Xiao, Y. (2019). Biochar impacts on phosphorus cycling in rice ecosystem. *Chemosphere*, 225, 311–319. Retrieved from https://doi.org/10.1016/j.chemosphere.2019.03.069

Xu, Q., Chen, Z., Wu, Z., Xu, F., Yang, D., He, Q., … Chen, Y. (2019). Novel lanthanum doped biochars derived from lignocellulosic wastes for efficient phosphate removal and regeneration. *Bioresource Technology*, 289(April), 121600. Retrieved from https://doi.org/10.1016/j.biortech.2019.121600

Yang, H., Ye, S., Zeng, Z., Zeng, G., Tan, X., Xiao, R., … Xu, F. (2020). Utilization of biochar for resource recovery from water: A review. *Chemical Engineering Journal*, 397(February). Retrieved from https://doi.org/10.1016/j.cej.2020.125502

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. *Environmental Science and Technology*, 47(15), 8700–8708. Retrieved from https://doi.org/10.1021/es4012977

Yin, Q., Zhang, B., Wang, R., & Zhao, Z. (2017). Biochar as an adsorbent for inorganic nitrogen and phosphorus removal from water: a review. *Environmental Science and Pollution Research*, 24(34), 26297–26309. Retrieved from https://doi.org/10.1007/s11356-017-0338-y

Yu, H., Zou, W., Chen, J., Chen, H., Yu, Z., Huang, J., … Gao, B. (2019). Biochar amendment improves crop production in problem soils: A review. *Journal of Environmental Management*, 232(September 2018), 8–21. Retrieved from https://doi.org/10.1016/j.jenvman.2018.10.117

Zelmanov, G., & Semiat, R. (2014). Phosphate removal from aqueous solution by an adsorption ultrafiltration system. *Separation and Purification Technology*, 132, 487–495. Retrieved from https://doi.org/10.1016/j.seppur.2014.06.008

Zhang, B., Chen, N., Feng, C., & Zhang, Z. (2018). Adsorption for phosphate by crosslinked/non-crosslinked-chitosan-Fe(III) complex sorbents: Characteristic and mechanism. *Chemical Engineering Journal*, 353(May), 361–372. Retrieved from https://doi.org/10.1016/j.cej.2018.07.092

Zhang, H., Wang, X., Xiao, J., Yang, F., & Zhang, J. (2009). Enhanced biological nutrient removal using MUCT-MBR system. *Bioresource Technology*, 100(3), 1048–1054. Retrieved from https://doi.org/10.1016/j.biortech.2008.07.045

Zhang, M., Song, G., Gelardi, D. L., Huang, L., Khan, E., Mašek, O., … Ok, Y. S. (2020). Evaluating biochar and its modifications for the removal of ammonium, nitrate, and phosphate in water. *Water Research*, 186. Retrieved from https://doi.org/10.1016/j.watres.2020.116303

Zhang, T., Xu, H., Li, H., He, X., Shi, Y., & Kruse, A. (2018). Microwave digestion-assisted HFO/biochar adsorption to recover phosphorus from swine manure. *Science of the Total Environment*, 621, 1512–1526. Retrieved from https://doi.org/10.1016/j.scitotenv.2017.10.077

Zheng, Y., Wang, B., Wester, A. E., Chen, J., He, F., Chen, H., & Gao, B. (2019). Reclaiming phosphorus from secondary treated municipal wastewater with engineered biochar. *Chemical Engineering Journal*, 362(December 2018), 460–468. Retrieved from https://doi.org/10.1016/j.cej.2019.01.036