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Editorial: Let's Talk About P(ee)

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Abstract

Practitioner points

- Phosphorus recycling and reuse are imperative, and the water industry has an important role to play in this effort.
- Technologies capable of removing phosphorus to ultra-low levels and subsequent recovery for phosphorus reuse are needed.
- Inorganic ion exchange resins and organic bioadsorbents are promising for phosphorus removal and recovery as part of the waste-to-resource paradigm.

Our *Water Environment Research* (*WER*) readers and authors are certainly not squeamish about discourse on topics that may well be considered taboo dinner conversation by others. Indeed, searching 2020 *WER* articles for those including at least one of the terms *manure*, *feces*, *urine*, or *wastewater* returned 273 results. But we can, and need to, do better. Specifically, activities in this sector have major implications for the broader global community in terms of environmental and public health goals, making it crucial to enhance broader awareness. One issue in particular that is not necessarily at the forefront of everyone's minds (but arguably should be high on the list) is "the phosphorus problem no one is talking about" (Doogue, **2021**).

Paradoxically, we have too much P, but also too little of this valuable nutrient. As an essential element to support all lifeforms, the majority of the world's mined rock P is used to support the global food supply. However, along the path from mine to field to fork, about 80% of that P is lost, thereby contributing to widespread water pollution such as eutrophication and harmful algal blooms (Cordell et al., **2009**). Many believe cultural eutrophication to be the most pressing surface water problem both now and in the future (Downing, **2014**; Smith & Schindler, **2009**). The juxtaposition of excess P entering environmental waters against the finite, depleting, and non-substitutable mineable P reserves is stark. Although there is wide variability in estimates of the timeline to reach peak P production, the time at which it will no longer be technically and economically feasible to continue to mine P deposits, there is absolute consensus that the rate of P extraction far exceeds the rate of natural replenishment (Cordell et al., **2009**; Doogue, **2021**). Beyond questions of *how much P there is* and *how long it will last*, the question of *where is it* confounds the situation as only four countries hold roughly 83% of the world's easily exploitable P (Vaccari, **2009**). Accordingly, P recycling and reuse are imperative.

Although human wastewater accounts for only about 15% of the lost P (Rittmann et al., **2011**), it offers a tremendous opportunity to capitalize on the dual benefit of P removal and recovery to support a circular P economy. To make this a reality, we need improved technology, better business models, system-level assessments, favorable regulations and incentives, and broad education to facilitate public awareness and acceptance (Mayer et al., **2016**). A range of technologies exist for P removal and recovery (e.g., as reviewed by Batstone et al., **2014**; Mayer et al., **2013**; Morse et al., **1998**). Yet, advancements capable of achieving P removal to the ultra-low levels (e.g., low μg/L) targeted in P-sensitive areas are needed given that current technologies often struggle to achieve stringent discharge limits (Beaudry & Sengupta, **2021**). Additionally, the circular P economy demands technologies capable of recovering the P in a pure, concentrated form suitable for agricultural reuse.

Reversible sorption-based processes offer one promising approach (Beaudry and Sengupta, **2021**), which is further buoyed by the potential for fundamental materials research to develop new technologies and systems that allow us to better remove, recover, and reuse P (Jones et al., **2020**). Sensitive P-selective adsorbents such as inorganic ion exchangers (e.g., Blaney et al., **2007**; Mullen et al., **2019**; Sengupta & Pandit, **2011**; Williams et al., **2015**; Zhao & Sengupta, **1998**) and bioadsorbents (e.g., Hussein et al., **2020**; Venkiteshwaran et al., **2018**, **2020a**, **2020b**; Yang et al., **2016**) have been developed and tested for this purpose. The May 2021 Editor's Choice article *Phosphorus recovery from wastewater using pyridine-based ion-exchange resins: Role of impregnated iron oxide nanoparticles and preloaded Lewis acid (Cu^{2+})* by Beaudry and Sengupta (**2021**) further advances development, understanding, and implementation of P removal and recovery from wastewater using P-selective ion-exchange resins.

Beaudry and Sengupta (**2021**) studied the performance of three different hybrid ion exchangers consisting of a pyridine-based polymeric base material modified with varying combinations of impregnated hydrated ferric oxide (HFO) nanoparticles and preloaded Cu^{2+} serving as a Lewis acid.

They explored the thermodynamics and kinetics of the ion-exchange materials, including evaluating binary separation factors, multiple kinetic models, and the intraparticle diffusivity of P uptake. All three ion-exchange resins tested (DOW-HFO, DOW-Cu, and DOW-HFO-Cu) provided selective P removal over competing ions and were able to achieve effluent concentrations <6 µg/L in fixed-bed column tests. Resin regeneration using NaCl and NaOH enabled precipitation of high-purity struvite crystals suitable for use as a slow-release fertilizer.

Importantly, Beaudry and Sengupta's results bolster understanding in the field of P recovery from wastewater, helping us to advance toward a circular P economy. Dr. Dana Cordell noted in a recent interview that "Phosphorus is essential to all life on earth, yet it doesn't seem to be anyone's responsibility" (Doogue, **2021**). The wastewater sector certainly has a vested interest and continues to step up to shoulder some of that responsibility. We can each assume additional responsibility by continuing to talk about P(ee) while designing and implementing solutions to better capitalize on the wastewater industry's waste-to-resource gold mine.

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