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Supporting Information

ABSTRACT: Phosphorus (P) is a critical, geographically concentrated, nonrenewable resource necessary to support global food production. In excess (e.g., due to runoff or wastewater discharges), P is also a primary cause of eutrophication. To reconcile the simultaneous shortage and overabundance of P, lost P flows must be recovered and reused, alongside improvements in P-use efficiency. While this motivation is increasingly being recognized, little P recovery is practiced today, as recovered P generally cannot compete with the relatively low cost of mined P. Therefore, P is often captured to prevent its release into the environment without beneficial recovery and reuse. However, additional incentives for P recovery emerge when accounting for the total value of P recovery. This article provides a comprehensive overview of the range of benefits of recovering P from waste streams, i.e., the total value of recovering P. This approach accounts for P products, as well as other assets that are associated with P and can be recovered in parallel, such as energy, nitrogen, metals and minerals, and water. Additionally, P recovery provides valuable services to society and the environment by protecting and improving environmental quality, enhancing efficiency of waste treatment facilities, and improving food security and social equity. The needs to make P recovery a reality are also discussed, including business models, bottlenecks, and policy and education strategies.

1.0. INTRODUCTION: MOTIVATION FOR TOTAL VALUE RECOVERY

The Green Revolution has enhanced global food production and made it possible for the Earth's population to exceed 7 billion people. A downside of modern agriculture is that it depends on massive inputs of fertilizers, including phosphorus (P), which is mined at a global rate of around 20 million metric tonnes of P per year.[1] Today, almost all of the P used in agriculture comes from mines located in just six countries that have P-rich deposits. While the world's supply of mined P is sufficient for many years and is not about to be depleted immediately, its geographic concentration creates political and economic risks for the vast majority of countries, which must import all or almost all fertilizer P. The risk is especially severe for low-income countries, in which fertilizer is a large proportion of the total cost of food production.[2]

An even more pervasive risk for P use in agriculture arises because only about 16% of the P applied as fertilizer makes it into human food.[3,4] Large fractions are lost to soil erosion, animal wastes, and crop residues. Moreover, the P that is consumed in food typically exceeds nutritional requirements, resulting in very little average assimilation,[5,6] with the remainder going to wastewater treatment plants. To varying extents, this "lost P" ends up as water pollution that spurs eutrophication, or the over-fertilization of water in lakes, reservoirs, estuaries, and the open ocean. Over-fertilization is the cause of hypoxic "dead" zones (as in the Gulf of Mexico and about 400 other locations worldwide[7]), widespread toxic

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Figure 1. Infographic summarizing major global drivers for P recovery and reuse as well as key products (P in addition to N, water, energy, and metals) and services (protecting and improving water quality, improving the operation of waste treatment operations, and enhancing social equity) supporting total value recovery.

cyanobacteria blooms, and loss of fish habitat. For inland waters, eutrophication decreases the value of lakes and rivers for recreation and can promote harmful algal blooms that impair municipal water supplies by adding unpleasant tastes and odors or by direct toxicity (e.g., microcystin and other toxins[8,9]).

An obvious way to reduce the risks to agriculture and water quality is to recover and reuse the lost P.[3,10] For agriculture, being able to recycle P back to a local or national food system minimizes P supply risks due to high prices or geopolitical disruptions, such as war or embargo. For water quality, recovering P instead of losing it as water pollution combats the devastating impacts of over-fertilization and its deterioration of water for many human uses, as well as maintaining a healthy aquatic ecosystem. Thus, recovering lost P provides a "double benefit." Despite the double benefit, little P recovery is currently practiced, largely due to economic constraints.

Today, the cost of recovering P from wastewater is several times higher than the market price of rock phosphate.[11,12] Experience with full-scale wastewater treatment plants in Japan shows that the income from struvite (magnesium ammonium phosphate, $MgNH_4PO_4 \cdot 6H_2O$), the most common form of P recovered from wastewater, accounts for only about one-third of the cost of the chemical inputs alone.[13] The problem is not that the cost of producing struvite from wastewater is exorbitantly high, but that the value of the single product, struvite, is too low to compete against the relatively low cost of mined P. However, when the total value of P recovery is accounted for, including products and services, additional incentives emerge in support of P recovery and reuse.

Phosphorus-containing waste streams span phosphogypsum waste from mining, agricultural runoff, animal manures, food and food-processing wastes, municipal wastewater, and sewage sludge.[4] Some of these P-containing streams also contain recoverable value in the form of water, carbon/energy, nitrogen, and metals.[14,15] For example, anaerobic digestion of waste biomass (e.g., crop residues, food waste, wastewater sludge) can produce biogas for energy and supernatant from which phosphate mineral fertilizers can be produced.[16,17] Municipal sewage sludge also can be mined for high-value metals, such as gold, silver and titanium.[15,18] Thus, other valuable materials from P-containing waste streams can augment the economic value proposition.

P recovery also provides services that are not readily monetized, but are significant to society. These include protecting and improving water quality, improving the operation of wastewater treatment plants, and improving social equity. For example, P recovery from wastewater or sewage sludge decreases the discharge of P to receiving waters, which decreases the potential for eutrophication and excess microbiological growth.[19] P recovery via struvite precipitation in anaerobic digestion liquors decreases the potential for scaling in pipes and pumps, which can improve sludge handling operations during wastewater treatment[20] and extend the life of the facilities. Finally, P recovery provides a local source of fertilizer. In industrialized countries, this may reduce the cost of P to farmers, and in the developing world, where the cost of mined P is higher, P recovery may also increase crop yields and contribute to food security.[21] Thus, P recovery and reuse provides valuable services to the environment and society

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augmented by the value from co-recovery of valuable materials along with P. Figure 1 summarizes some of the major drivers for P recovery, as well as the products and services supporting the total-value approach.

1.1. A Roadmap to Total-Value Recovery. This article provides a comprehensive overview of the different values that come from recovering P from waste streams, i.e., the total value of recovering P. To begin, high-value products that come from the process of P recovery are identified. Besides P itself, other materials associated with P can be recovered in parallel to provide additional benefits. Next, the services that come from P recovery are discussed. These mainly involve improving environmental quality, but they also can enhance the efficiency of waste-generating operations, such as in concentrated animal feeding operations (CAFOs), in addition to improving food security and social equity. Next, the business model of P recovery is addressed: how to turn the various values of P recovery into a commercial success. Part of the business model is identifying bottlenecks where technology innovations are needed, and promising avenues in these areas are outlined. Finally, policy and education strategies essential for making P recovery socially acceptable are broached.

2.0. PRODUCTS

While no single solution can replace massive consumption of phosphate rock, sustainable conversion of "waste" from the lost P flows to valorized products is an important step toward closing the loop.[22−25] Re-envisioning waste treatment systems as *Resource Recovery Facilities* can contribute to this effort.[26] This new paradigm emphasizes recovery of nutrients (P, N), energy, and water; additionally, recovery of other minerals such as K, Ca, and Ag, as well as organics facilitates total value recovery.[25]

2.1. The P Itself−A Renewable Fertilizer or Industry Feedstock. Phosphorus is a "strategic" commodity in the global marketplace.[25] In the words of Isaac Asimov (1974),[27] "life can multiply until all phosphorus is gone, and then there is an inexorable halt which nothing can prevent...We may be able to substitute nuclear power for coal, and plastics for wood, and yeast for meat...but for phosphorus there is neither substitute nor replacement." Globally, agricultural food production is the dominant domestic P flow, accounting for approximately 90% of mined phosphate rock.[4,28,29]

2.1.1. P Incorporated in Sewage Sludge and Organic Waste. Currently, the primary means of agricultural reuse of wastewater-derived P is through effluent reuse and land application of sewage sludge.[22] Processes such as chemical precipitation and enhanced biological phosphorus removal (EBPR) can efficiently incorporate P into solids, which can be land-applied to agricultural soils and are widely recognized to improve soil properties.[22] Sewage sludge typically contains 2−3% P by dry mass, whereas EBPR sludge can contain 2−5 times more P.[30] The P from EBPR sludge can be as effective as mineral P,[31] but, depending on precipitation conditions, the P in sewage sludge may not be readily bioavailable due to binding with Al or Fe.[23,32] This is especially true when iron salts are intentionally used to remove P from wastewaters, making beneficial reuse impossible.

Land application is commonplace in many countries where sludge transportation is economical, but is also subject to regulation, and, in some instances, restrictions on the basis of heavy metals and/or organic micropollutants.[33] Unless incinerated, sewage sludge also contains large amounts of nitrogen (N), and application rates are often limited to the agronomic rate, or the amount of N that can be taken up by specific crops. Although estimates of agricultural reuse globally are scarce, available data indicate approximately 45% of sewage sludge is land applied in Western Europe (plus 7% for composting), 23−62% in Eastern Europe, 60% in Australia, and 55% in the U.S.[34,35] In many developing countries, on-site sanitation systems dominate and only larger cities generate sewage sludge, making national assessments difficult. However, reuse of sewage sludge as well as septage sludge, raw or composted, has been reported in a number of developing countries and emerging economies, including Brazil, Chile, China, Colombia, Ghana, India, Indonesia, Mexico, Philippines, Uganda, and Vietnam.[36]

Sewage sludge may be further processed for land application as soil amendments. Sewage sludge incineration is particularly popular in countries with scarce land resources, such as Japan, where more than 70% of sewage sludge is incinerated.[37] Although the ash of incinerated sludge is rarely land applied in the U.S., it is rich in P (4−11% P by weight[38]) and can often meet metals-applications standards if applied on the basis of P fertilizer requirements. For comparison, the P content of mined phosphate rock is ∼13% (average of 30.8% P_2O_5).[39] Incinerated sewage sludge ash (ISSA) also has the advantages of low weight (hence low transportation costs) and low N, which is beneficial in areas with high potential for groundwater nitrate contamination. Bierman and Rosen (1994)[40] have shown that ISSA can be a viable fertilizer. Additionally, biochars produced by slow pyrolysis may proffer benefits as soil amendments, including C sequestration, reduction in greenhouse gas (GHG) emissions, and slow release of P, N, and K for fertilization and soil conditioning.[41−43]

The use of compost and other organic solids as a soil amendment has a multitude of benefits, including improving water retention, promoting soil health, filtering pollutants, and supplying trace minerals.[44] Organic and other small-scale farms are more likely to rely on organic solids as a nutrient source than larger farms. Due to high transport costs, organic solids need to be used close to their source, which results in the large quantities produced in cities being used by homeowners, golf courses, parks, and landscaping companies, or dried and pelletized prior to shipment to reduce weight. The use of compost for urban vegetation not only represents cycling of P and other nutrients, but the buildup in urban soils can also create a pool for future use. The use of heterogeneous organic solids is an important part of a sustainable P system, and further processing to isolate P from these streams could add cost to an already successful business model and may remove other nutrients and characteristics that make soil amendments beneficial.

2.1.2. Separated P. Beyond land application of sewage sludge or other organic soil amendments, P recovery can be achieved through separation of P from the water, wastewater, solids, or ISSA. Today, most P-separation processes rely on precipitation/crystallization to recover phosphate minerals that can be used by the fertilizer industry, e.g., struvite or hydroxyapatite (HAP, $Ca_5(PO_4)_3OH$).[11] Additionally, P can be recovered using variations of acid-leaching and/or thermochemical methods to produce fertilizer products or P-rich industrial feedstocks.[38]

In addition to its use in the agricultural sector, P also is used in industries such as production of chemicals, food and beverages, iron and steel, pharmaceuticals, etching agents, flame

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retardants, and lithium-ion-phosphate electric-vehicle batteries.[45−47] Because recovered P is commonly free from contamination from heavy metals, radionuclides, and other impurities,[48−51] it may be especially valuable for these industries. However, additional processing (and therefore additional treatment costs) may still be required for these non-agricultural P uses.[46] HAP is a directly comparable substitute for rock phosphate[11] and has versatile applications in manufacturing, for example, bioceramics.[52] Alternately, struvite is typically used as a fertilizer rather than in the phosphate industry, since its ammonium and magnesium contents preclude processing via the industry's established technologies.[11,46,53] However, struvite can be used in fire-resistant panels and cement, and, as more economical production methods are developed, it could be used in products such as cosmetics and animal feed.[54]

2.2. Renewable Energy. Renewable energy (e.g., methane or hydrogen) from waste biomass is one of the valuable products that can be recovered from P-containing waste streams. A significant quantity of waste biomass is generated as a result of municipal wastewater treatment, agricultural operations such as CAFOs, forestry/pulp and paper industry, crop residues such as corn stover, and food processing.[55] Energy and nutrient value are currently recovered from only about 25−30% of the total available waste biomass,[56] and between 30−80% of N and 15−18% of P from a variety of livestock wastes are lost prior to any form of recovery.[57] This presents a tremendous opportunity for expanding the supply of renewable energy (available in the carbon, C) and nutrients (N and P) without altering existing food-supply systems. Simultaneously capturing energy and nutrients from waste biomass also can alleviate major problems related to environmental degradation associated with these wastes as spills from livestock manure storage facilities spawn major problems of nutrient contamination.[58] These dual objectives make waste biomass sources very attractive as potential candidates for resource recovery and biological waste treatment.[17]

The first step for simultaneous energy and nutrient capture from wet particulate biomass is hydrolysis of the complex organic solids and polymers. Hydrolysis can be accelerated by physical-chemical, thermal, and enzymatic pretreatment.[59] The result is enhanced bioavailability of the organic C, which boosts production of valuable energy products from anaerobic microbial technologies: methane (CH_4) from anaerobic digestion or anaerobic membrane bioreactors, electric power or hydrogen gas (H_2) from a microbial electrochemical cell (MXC), or H_2 and volatile fatty acids from fermentation. Hydrolysis and anaerobic biotechnologies mobilize a significant fraction of the nutrients from the particulate biomass to the liquid phase: N as NH_3−N and P as reactive orthophosphate (PO_4^{3-}), which are available for subsequent recovery.[26] Anaerobic digestion solubilizes 15−20% of the total P in the particulate organic wastes to the liquid phase, after accounting for losses to precipitation (at neutral pH).[60] This can be increased to 75% P solubilization using acid pretreatment (pH 4) followed by acid-phase digestion of waste activated sludge, albeit with a 50% decrease in methane production.[61] More effective pretreatment technology would operate at neutral pH to release soluble P and be readily coupled with anaerobic digestion to enhance energy capture as CH_4. Pretreatment also should improve the pathogen inactivation achieved with anaerobic digestion.[15,62]

After energy capture by anaerobic microbial technologies, the effluent is usually rich in humic, fulvic, and ionic organic components,[63] which can compete with P for adsorption sites, thereby interfering with recovery of P in downstream processes such as ion exchange.[64] Hence, efficient strategies may be needed to polish the effluent for full recovery of the mobile P. This may include polymeric ligand exchange based on high selectivity between iron oxide and phosphate,[65,66] perhaps in combination with selective advanced oxidation and biodegradation of the residual organic fraction to release more recoverable P.[3,67]

Globally, roughly 30−40% of food is wasted, although the underlying causes differ dramatically between the developed and developing worlds.[68] In developing nations, losses are mainly attributed to lack of food-chain infrastructure, for example, storage technologies,[68] whereas pre-retail losses are much lower in the developed world. In the U.S., the caloric content of food waste at the consumer level (i.e., grocery stores, restaurants, and homes) is about half of that consumed.[69] Organic wastes can be used for energy extraction through incineration, anaerobic digestion (separate or mixed with sewage sludge), and pyrolysis to form biochar, liquid fuels, and gases.[70,71] Anaerobic digesters create energy from organic wastes as their primary income (∼35% of economic gains), and the P and N-rich byproducts provide a second revenue stream (∼35%).[26] Food wastes also can be processed (dried, sterilized) to form feedstock to be blended into commercial animal feeds. Several key limitations of P recovery from food waste are their generally diffuse sources of origination and complex mixture of constituents. These barriers could be overcome by modifying food-waste collection, e.g., source separation to yield far higher potential value. For food wastes with low contamination, P could be recycled as animal feed, compost, or biochar resulting from pyrolysis.

2.3. Nitrogen. Recovery of N from wastewater is often considered a lower priority than energy or P recovery,[72] likely because N can be converted to readily removable N_2 gas during biological treatment. Moreover, the atmosphere supplies a ready reserve of N that can be recovered using the Haber-Bosch process. However, Haber-Bosch, which is used mainly for fertilizer production, is an energy-intensive process that accounts for approximately 1% of global energy consumption and substantial concomitant GHG emissions.[73−75] In addition, wastewater treatment plants use energy- and chemical-intensive processes, particularly nitrification/denitrification, to remove reactive N and N_2 gas.[76] Nitrification also can produce N_2O, which is a concern for GHG emissions.[76] Hence, as energy costs and GHG regulations increase, interest in N recovery will grow, offering the potential to satisfy approximately 50% of the global N market.[77]

To the extent that N is currently recovered with P (beyond that recovered in biosolids), it is most commonly recovered from digester supernatant or centrate together with P as struvite. However, struvite removes N and P in a 1:1 molar ratio. Since N is typically present in excess of the ratio, additional treatment is often needed to satisfy discharge permits. One approach to N recovery from domestic wastewater and other waste streams is ammonia stripping from anaerobic digestion liquor followed by an absorption step, possibly in combination with biogas production and struvite precipitation.[78] Other approaches to N recovery from wastewater require more radical changes such as urine source separation,[79] anerobic treatments (e.g., anaerobic membrane

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bioreactors) followed by nutrient recovery,[80] or re-engineering wastewater treatment plants to recover N as microbial protein for use as food and feed.[81]

2.4. Metals and Minerals. Together with P and N, recovery of K could supplement supplies of agricultural macronutrients. Yet, K recovery has attracted little interest, possibly due to the historically low pricing of potash (~$500 per ton) and reserves that are expected to last 330 years.[77,82] However, given that K is an essential macronutrient for plant growth,[83] K recovery from wastes could help satisfy global demand by replacing mineral K.[17,77,84] For example, K can be recovered from human urine as potassium struvite ($MgKPO_4 \cdot 6H_2O$),[66] which achieves co-recovery of P and K.

Domestic wastewater offers potential to recover nutrients, renewable energy, and also many metals that can significantly add to the total value proposition. Globally, an estimated 360 tons of Au accumulate in wastewater sludge annually.[18] A wastewater treatment plant in Suwa, Nagano, Japan reported nearly 2 kg of Au per ton of ISSA,[15] though this likely includes contribution from nearby industries. A survey of metals in U.S. municipal sludge found that Na, Ca, P, K, Mg, Fe, Al, and Ti were present in the greatest abundance, each at levels of 1−30 g/kg dry solids.[18] Several metals (Ir, Cd, Ag, Pd, Ru, Pt, and Au) were present in higher abundance relative to average soil in the earth's upper continental crust. Using an estimated market price for each element, the economic value of metals in sewage sludge was calculated at $460 per dry ton, with Au and Ag contributing about 20% of the total value and P contributing less than 1%. Magnesium could also offer economic potential, with potential recovery value about 8 times higher than P (but 8 times lower than Ag), assuming a maximum economic recovery scenario.[85] Based on concentration, enrichment in municipal wastewater compared to soil, and economic value, the most promising metals to recover were Ag, Cu, Au, P, Fe, Pd, Mn, Zn, Ir, Al, Cd, Ti, Ga, and Cr.[15,18]

In the future, metal concentrations in municipal sludge may increase as a result of trends in consumption. First, per capita wastewater production is declining due to conservation measures, but stable per capita pollutant loading is expected.[18] Second, the increasing manufacture and use of nanomaterials leads to inevitable increases of these materials in municipal wastewater.[86] Currently, ≥60% of the thousands of tons of nano-Ti and nano-Ag produced each year finds its way to wastewater treatment plants.[87,88] As nanomaterial production increases, concentrations of nano-TiO_2 in sewage sludge are predicted to reach 100−523 mg/kg in the U.S. and Europe.[88] This scenario may lead to a tipping point when exploiting the potential co-recovery of valuable materials such as metals and nutrients from sludge is more economical than land disposal.[18]

Thus, while few techniques for recovery of elements other than N or P have been demonstrated,[15] future trends may provide additional incentive to develop and implement treatment processes focused on total-value recovery. For example, oxidation may liberate organically bound P and N, release colloidal or organic-bound metals to facilitate downstream recovery, and increase pathogen inactivation and degradation of organic contaminants of concern.[15] Mulchandani and Westerhoff (2016)[89] reviewed technologies to separate and recover metals from sewage sludges, potentially with the opportunity to simultaneously recover energy in the form of liquid biofuels. Incineration followed by acid leaching and metal separation was the most energy intensive process. Lower energy processes would lyse cells to release metals using pyrolysis, gasification, or oxidation. Techniques to achieve liquid extraction of metals from sewage solids may include solvent-liquid extraction or supercritical carbon dioxide extraction for lipids and/or metals. Hydrothermal liquefaction can reduce sludge volume by approximately half, with substantial conversion of the liquefaction products to liquid biofuel and concentration of nearly all of the P and metals into a small amount of residual char. The char could then be treated by acid leaching and thiourea or other ligands to separate high-value metals (e.g., Au and Ag), whereas P and K could also be recovered from the residuals.[89]

2.5. Water. At the confluence of mega-issues such as global climate change, shifting demographics and land use, and increasing population and urbanization, the availability of adequate supplies of high-quality water remains a global priority in terms of human and environmental health.[90] Of all of the products from Resource Recovery Facilities, water arguably is the most important.[72,91] While widespread application of resource recovery in terms of energy, nutrients, and other materials is a more recent focus, production of high quality water to limit environmental degradation and protect public health has been the focus of wastewater treatment from the outset.[72]

While many nations recycle water to some extent, most currently recycle less than 10% of total wastewater flows. However, as shown in Figure S1 in the Supporting Information (SI), water-stressed regions, such as Israel, are increasingly leveraging substantial fractions of municipal wastewater to augment water resources with reused water.[92,93] Correlation statistics (description in SI) show that water reuse significantly correlates to water risk ($p = 0.0005$, risk being characterized by water quantity and quality indicators as well as regulatory and reputational risk indicators, as described in the SI), whereas no correlation was found with economics (gross national income [GNI] per capita), human development index (HDI), and education (expected years of schooling). Thus, despite qualms and negative perceptions of using wastewater, societies practice reuse when they must (which tends to drive P recovery), and this is an indicator of the future trend for total-value recovery.

The clear historical preference has been toward nonpotable wastewater reuse, with the greatest volume disbursed to agricultural irrigation, followed by industrial recycling and reuse, landscape irrigation, groundwater recharge, recreational and environmental uses, nonpotable urban uses, and finally potable reuse.[94−96] As most recycled wastewater is used for irrigation, the nutrient content of the recycled wastewater can be a source of nutrients, that is, fertigation.[97] In certain cases, irrigation with recycled wastewater can provide all of the nutrients needed by crops and add value through cost savings to farmers. This is particularly applicable when using secondary treatment or less in an arid setting with high irrigation rates, for example, 11% and 29% of reused wastewater was used on crops in California and Florida, respectively, in 2009.[98] Regulatory compliance is essential in these cases, and reuse is typically limited to non-edible crops.

Although lagging behind nonpotable reuse, potable water reuse is a future imperative, as the convergence of water stressors makes the tapping of new water supplies increasingly difficult, if not impossible, in metropolitan areas.[95] Direct potable reuse has been practiced for nearly 50 years in Windhoek, Namibia, and is sufficient to satisfy approximately 35% of the city's water demand.[99] Direct potable reuse also has been implemented more recently in locations such as Wichita

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Falls and Big Springs, TX, where water stresses have overridden perception issues.[99] Indirect potable reuse, both planned and unplanned, is practiced around the world and is particularly prevalent in the U.S., Europe, and Singapore (home of the "four national taps" strategy).[24,100] The emerging international trend toward potable water reuse[101,102] dictates substantial reductions in contaminant loadings. This is likely to be a strong driver for removal and recovery of P, N, and other valuable materials, along with the water, in order to expand the product portfolio and help offset higher treatment costs.

3.0. SERVICES

The history of P removal from wastes is rooted in services to the environment and society. These difficult-to-monetize services provide great value and can be influential drivers for implementing resource recovery. They include protecting and improving water quality, improving operation and performance at waste treatment facilities (wastewater treatment plants as well as landfills), and improving food security and social equity.

3.1. Protecting and Improving Water Quality. P fluxes to the environment are primarily affected by regulations targeting protection and improvement of water quality. As the limiting nutrient in most freshwaters, P controls photosynthetic productivity. When present at excess levels, it can promote eutrophication, or accelerated aging of a water body,[3,103] which is the most prevalent global water quality problem.[92] Eutrophication seriously degrades environmental waters by altering water chemistry and aesthetics, shifting the composition and diversity of aquatic species, decreasing biodiversity, limiting recreational use, and restricting navigation.[104] These changes can cause major ecological damage: for example, the more than 400 coastal dead zones at the mouths of rivers discharging P.[7] Additionally, eutrophication can have substantial economic and social repercussions, for example, loss of fisheries and resulting job losses.[105] As a result, limitations on nutrient concentrations in environmental waters are imposed by many governing bodies, with some as low as 5−10 μg/L.[103,106] The emergence of ultra-low regulations/guidelines in P-sensitive environmental systems (e.g., the Everglades, Great Lakes region, and Spokane River) in turn dictates increasingly lower effluent P concentrations in point source discharges. For example, NPDES (National Pollution Discharge Elimination System) permits for allowable effluent P concentrations recently dropped to μg/L levels in some parts of WI, U.S., in response to revised P regulations, which reduced total maximum daily loads (TMDLs).[107,108] As a result of such regulations, many wastewater treatment systems located upstream of impaired waters are now required to utilize advanced P removal to increase from as little as 20−40% P removal[109] up to 90%. Although focused primarily on P removal to protect environmental water quality, these regulations also promote P recovery as the cost for recovery may be a marginal increase over costs of removal and also include multiple benefits, or total value recovery.

Clear, aesthetically pleasing water attracts recreational use and the economic benefits associated with use and tourism, and it promotes higher values for adjacent properties, even those up to 1.2 km from the shoreline.[110−113] Several studies have used hedonic analysis to relate water clarity (a surrogate for algal density) and property value.[111,114−117] The economic impact of a loss of 1 m clarity can range from a few percent to as much as 34%.[115] Surveys report that clarity influenced nearly half of respondents' purchasing decisions.[117] Additional costs associated with eutrophication of surface waters include increased water treatment, loss of recreational value, and reduced value of commercial fisheries. Economic damages associated with cultural eutrophication of freshwaters is an area of current research, and has been estimated at $2.2 billion annually in the U.S. alone, the greatest portion of which is attributed to economic losses in lakefront property values.[110] The total value of the ecosystem disservices of freshwater and estuarine eutrophication has yet to be determined, but is certainly much larger.

3.2. Improving Operation and Performance at Waste Treatment Facilities. Significant savings may be attained through P recovery from wastewater due to decreased costs of sludge handling and disposal in relation to the larger sludge volumes generated during P removal via chemical precipitation.[118] Further operational benefits that may be realized include reducing reliance on chemicals for P precipitation (e.g., alum) and alleviating cleaning requirements for spontaneous struvite precipitates formed during or following anaerobic digestion.[118] In fact, struvite precipitation originated as a means to combat struvite scaling, rather than to provide a means of P reuse. Struvite fouling was first recognized as an operational impedance in 1939 and continues to be a costly issue (approximately ≥ $100,000/yr for a 25 MGD treatment plant) in municipal and animal wastewater treatment operations.[119,120] The issue has been amplified as increasing numbers of facilities implement advanced P removal, for example, EBPR, to satisfy discharge regulations.[121]

Operation and performance at landfills can also benefit from P recovery. As they comprise up to 40% of municipal waste,[122] diverting organics from landfills can dramatically extend the useful life of a landfill and reduce CH_4 production (landfills produce ∼16% of total CH_4 emissions). While the economics of organic waste management are often driven by tipping fees, some locales are adopting policies requiring that organics be diverted from landfills as a sustainability measure. The Food Waste Challenge, implemented in the U.S. in 2015, set a goal of 50% food waste reduction by 2030.[123] The P recovered from waste in the Twin Cities, MN, coupled with improved P use efficiency and dietary shifts, could satisfy 50% of the local food production requirements.[124] Such efforts, together with climbing landfill fees, will likely motivate increased recycling of food waste and the inherent P.

3.3. Improving Food Security and Social Equity. Waste-derived nutrient recycling can advance several of the United Nations' Sustainable Development Goals.[125] These include eradicating poverty and hunger, achieving food security and improved nutrition, promoting sustainable agriculture, ensuring sustainable consumption and production patterns, and ensuring availability and sustainable management of water and sanitation for all.[4,125,126] P recovery may promote poverty relief through (1) reduced fertilizer costs, allowing for reallocation of those expenses, (2) reduced malnutrition due to improved nutritional variety and household food security, and (3) increased income from surplus crop marketing.[22,127] Thus, recycling P to agriculture, together with the associated co-benefits, contributes to sustainable development in general[128] and social equity in particular,[129] which is defined as the balancing of benefits and burdens by all citizens.

As of 2011, 2.5 billion people (36% of the global population) lacked access to improved sanitation.[130] Re-envisioning municipal wastewater management to focus on resource recovery provides a new opportunity to improve sanitation.

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Environ. Sci. Technol. 2016, 50, 6606−6620

One such approach is urine source separation, which has been proposed as an alternative to conventional centralized wastewater management because of the opportunity to recover nutrients. Urine-diverting toilets can provide improved access to sanitation in addition to the added benefit of recovering P and other nutrients for use as fertilizer, for example, struvite.[21,131] Alternatively, stored urine can be applied directly as fertilizer, which has been shown to produce similar crop yields compared to synthetic fertilizer and much greater yields versus no fertilizer addition.[131]

Direct benefits in terms of food security and diversifying P sources can make recovered P a prominent player in geopolitical stability.[4] By attenuating reliance on rock P, recovered P may alleviate tensions triggered by looming P scarcity. For example, in 2007−2008, rising food prices sparked riots in more than 40 countries, which may have arisen, at least in part, due to escalating fertilizer prices.[132] In India, scarcity of fertilizers has been directly blamed for riots.[4] Converging concerns over peak P, peak oil, water scarcity, and climate change have certainly captured the world's military strategists' attention.[25,133]

4.0. NEEDS TO MAKE TOTAL VALUE RECOVERY A REALITY

The issue of P recovery falls into a class of problems for which improved technology is necessary, but not sufficient.[134] Technological advances must be integrated with improved business models, systems-level understanding, policy support, and increased public awareness and acceptance. Implementation of P recycling and reuse requires an approach that involves total value recovery at local, national, and international scales.

4.1. Improved Technology. A number of existing and emerging P-recovery technologies are described in detail in several excellent reviews.[3,11,32,46,54,77,135] Technological improvements will facilitate P recovery from various sources (i.e., not solely municipal wastewater) in a range of settings (e.g., developed vs developing world context). Technologies must also be designed with a focus on the end products (i.e., what are agricultural needs?) and enhancement of total value recovery rather than focusing on recovery of only a single P product.

To substantially satisfy P demands, we must recycle close to 100% of the P flows now lost in the anthropogenic cycle.[25] This will involve new technologies (for products and processes) targeting liquids and solids,[136] including erosion and drainage (46% of mined P), animal waste (40% of mined P), municipal waste (15% of mined P), and industrial waste (input of 15% of mined P).[3,4] Note that percentages are based on mined P input; because of other inputs to the food system, e.g., recycled P residues and P contained natively in the soil, they do not sum to 100%. Until relatively recently, agricultural use of sludge offered the sole pathway to recycle the P in municipal wastewater back to productive land.[137] Today, innovative physical, chemical, and biological technologies are being developed to allow P capture and recycling from a diverse range of sources, including nonpoint sources and surface waters;[103,138] animal waste;[3] industrial waste; and municipal wastewater—mainstream wastewater, sewage sludge, and ISSA.[11,137] Given that nonpoint sources are more difficult to intercept and treat, the natural starting point is infrastructure designed to recover waste P from animal, municipal, and industrial point sources.[3]

Non-incremental technological improvements beyond current P-recovery practices are essential for total value recovery; that is, P removal alone or recovery of only a single product, for example, struvite, will not improve the economics sufficiently. For example, chemical P precipitation imposes a net environmental burden as the displaced fertilizer production does not fully offset the life cycle impacts of the chemical inputs.[139] Figure 2 illustrates that numerous processes are being

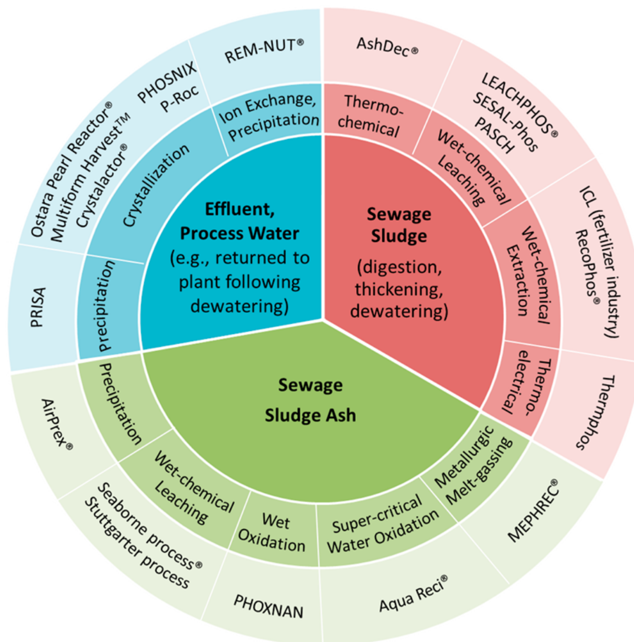

Figure 2. Examples of established wastewater P recovery technologies, identified by Egle et al. (2014).[140]

developed and tested for P recovery from various wastewater streams, including the liquid itself (effluent or sludge dewatering stream), the solids, and ISSA. While these systems are being deployed at varying scales, none is as yet widely adopted. New, disruptive technological developments that create portfolios of valorized products are advantageous for justifying technology implementation on the basis of net total value (of which the value of the P product alone may constitute a small fraction). As new technologies are translated to practice, desirable attributes include reduced costs and inputs of energy and chemicals, higher purity products (e.g., by more selective capture of resources), co-recovery of other resources, production of readily manageable products (e.g., transportable, storable, amenable for field application), and locale-appropriate operation.

Fertilizer is by far the largest P market, and opportunities are great to recover more agriculturally favorable products using reduced energy and chemical inputs. Increasing urbanization and specialization in agricultural production present spatial challenges for connecting sources of recovered P to areas of agricultural activity;[3,22] thus, processes that produce a more readily transportable fertilizer input are critical (e.g., high P concentration, low water content). While sewage sludge and other organic soil amendments, struvite, and HAP are fairly well-established P products for agricultural use, technological advances in high P-affinity sorbents with extended lifespans and reduced chemical requirements will lead to more economically attractive products.[141] For example, struvite does not provide

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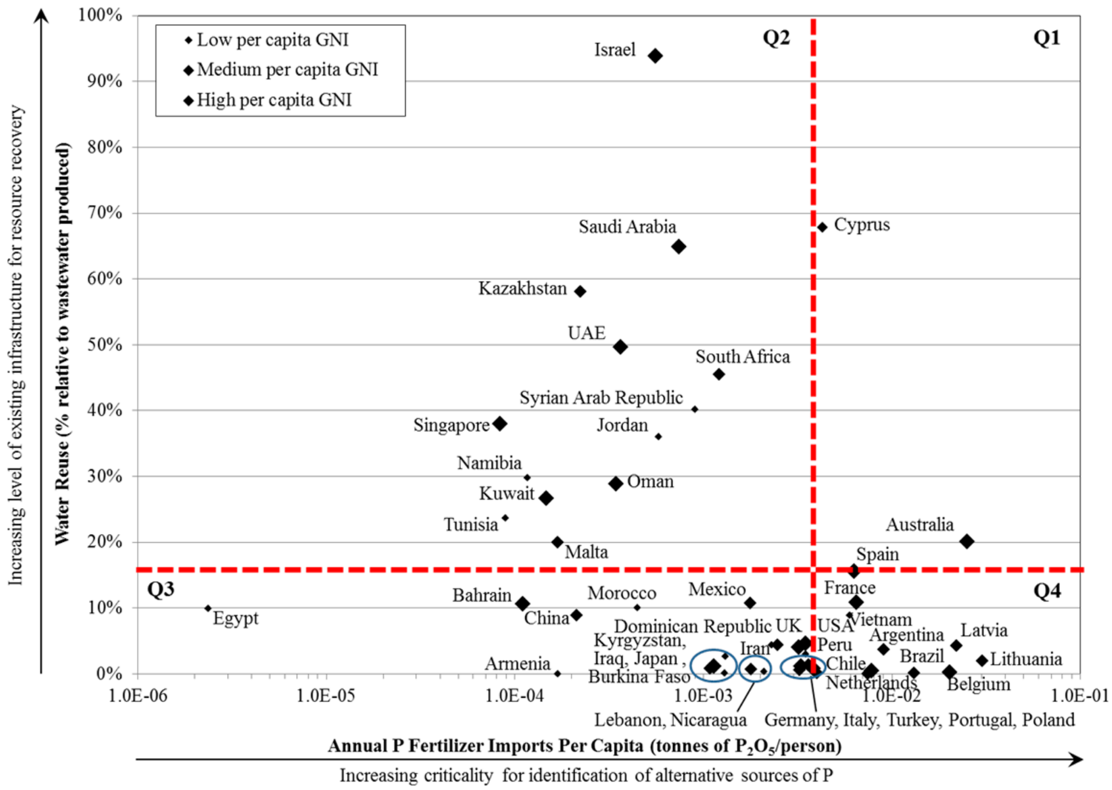

Figure 3. Analysis of relative opportunities to recover P from municipal wastewater. Water reuse data were calculated relative to total domestic wastewater produced, using the most recent data available.[148] Phosphate fertilizer imports were reported by the United Nations' Food and Agricultural Organization (FAO)[149] and population was taken from the World Bank.[150] Quadrants were defined using the average of each axis. The small-sized symbols represent the lower one-third of gross national income (GNI) per capita[151] reported for countries in this data set (<\$12,000). The medium-sized symbols represent the middle third, \$12,000 ≤ GNI per capita < \$30,000. The large-sized symbols represent the upper third, GNI ≥ \$30,000.

the optimal N:P ratio for the nutritional needs of plants, nor is it the favored raw material for fertilizer production.[142] Thus, product value can be increased using more selective recovery technologies, for example, ion exchangers, which feature flexibility to control product nutrient content using the highly concentrated P and/or N regenerant streams. Likewise, P and N may be better separated and concentrated using emerging technologies such as electrodialysis.[26] Challenges with these technologies that must be overcome prior to widespread deployment include minimizing competition with co-occurring ions and organic matter, and reducing costs for material and energy inputs.[26]

As future technologies are developed, total-value recovery is an essential guiding principle. One approach that offers great promise is coupling effective pretreatments with anaerobic biotechnology such that soluble P is released while simultaneously enhancing energy capture. For example, a pre-oxidation step offers multiple advantages of mineralizing P and N, increasing energy capture, releasing metals from complex wastes, and inactivating pathogens. Additional research must reduce energy inputs and demonstrate these integrated technologies at larger scales.

In line with the new paradigm of resource recovery and reuse, sustainable and locale-appropriate technologies are needed for the developed and developing worlds. They must deliver high-value products from a range of flows while satisfying sanitation and environmental objectives.[22] For example, source-separated urine often is a good starting point for fertilizer products.[6,22,143] In addition to the majority of the N, urine may contain 25−67% of the P in domestic sewage, predominantly in the bioavailable, more readily recoverable inorganic-ion form. Small-scale and large-scale struvite precipitation from source-separated urine has been piloted in many countries, including South Africa, Sweden, The Netherlands, and Nepal, although the yields are relatively low (about 1 kg struvite from 500 L urine, roughly 40% P recovery efficiency assuming 1.4 L urine/day[144] and 0.3 kg P/year[22]). Less-developed regions, where sewerage infrastructure is lacking, are more conducive for urine source separation in the near term, whereas regions with extensive existing sanitary infrastructure would need to retrofit existing systems to the resource-recovery model.[22] Source separation enables synergistic value recovery through improved sanitation in the developing world by reducing contact with pathogens in organic waste, providing a local source of fertilizer, and simultaneously capturing N.

4.2. The Business of P Recovery from Waste. The closed-loop paradigm (or circular economy) emphasizes total-value recovery that replaces nonrenewable sources. Accordingly, business models are emerging to harness economic opportunities in value creation from the recovery and reuse of resources that would otherwise be irretrievably lost.[99,145] Business models are emerging at different scales, ranging from community composting and low-cost struvite recovery from urine-diverting toilets to industrial recovery in CAFOs and wastewater treatment plants. In developing countries, resource recovery from wastewater (e.g., using urine-diverting toilets) may allow the free market to support small businesses that collect and treat waste and then recover and sell the value-

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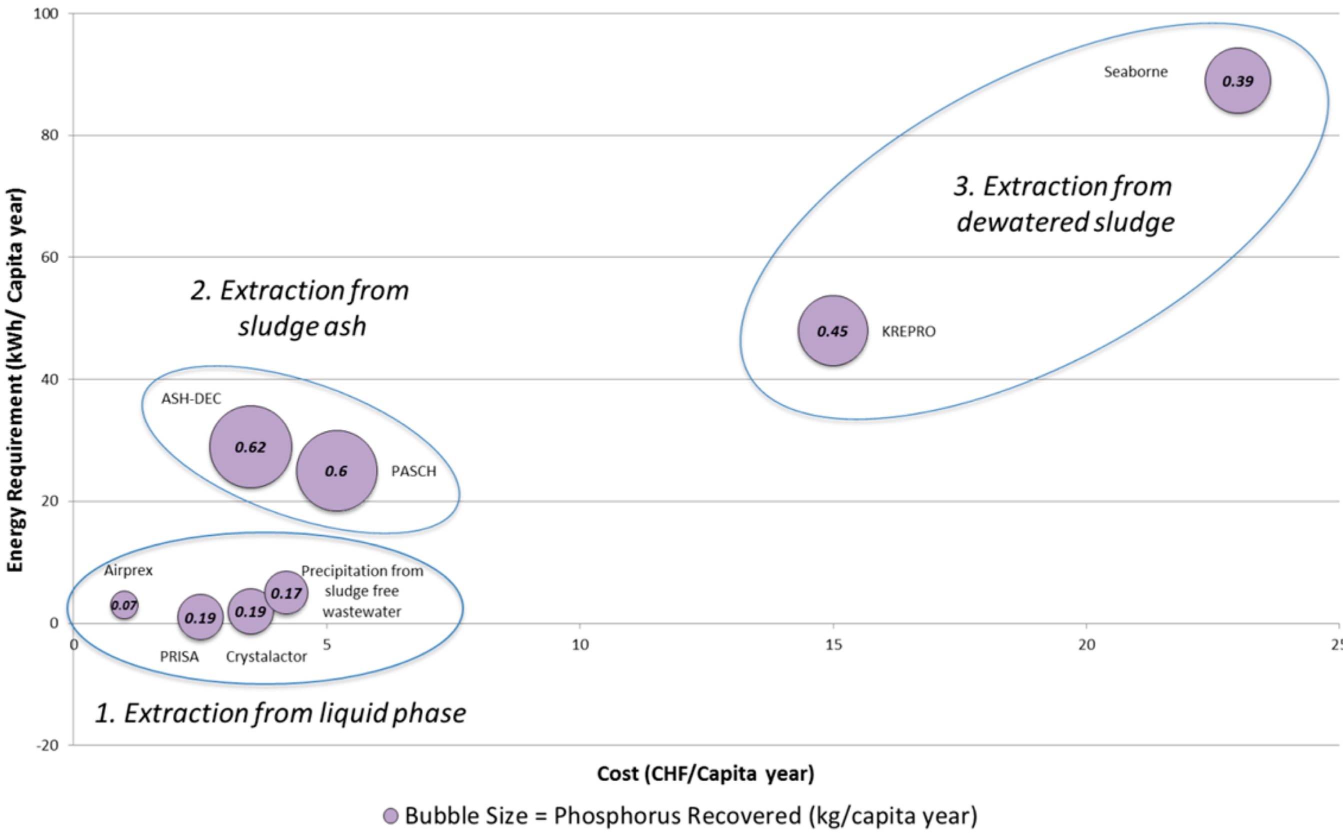

Figure 4. Energy requirements versus total costs (CHF = Swiss franc ∼ US$) of different P recovery technologies for wastewater treatment plants, modified after Morf and Koch (2009).[152] The costs refer to Swiss conditions and include personnel, operations, raw materials, energy, and interest payments. The energy requirements consider gas, electricity, external (e.g., thermal) power, and the energy needed to produce the required raw materials, which are mostly chemicals. P recovery is in reference to the total amount entering the wastewater treatment plant.

added products.[21] In this context, market-driven implementation is likely the only mechanism for widespread application of P-reuse technologies.[146] Since the sale price of the recovered struvite relative to rock P-derived fertilizers is too low to justify struvite recovery on economic arguments alone, recovery in large-scale wastewater treatment plants is driven by cost avoidance of removing P, which limits damage caused by struvite precipitation in valves and pipes.[147]

In some cases, reusing recovered P as part of a complex matrix, for example, organic solids or water, rather than separating it as a chemical fertilizer product, can offer major benefits. In particular, use of compost and other heterogeneous organic solids can offer a successful business model, making P separation unnecessary as it adds cost and could remove beneficial aspects of the product as a soil amendment. Likewise, P in treated wastewater reused for irrigation can provide a successful business model in certain scenarios.

Figure 3 presents a quadrant analysis depicting relative opportunities to recover P from municipal wastewater, where P need (quantified as annual P fertilizer imports) is shown on the *x* axis and wastewater resource-recovery infrastructure (quantified as percentage of wastewater reuse) is shown on the *y* axis. In section 2.5, lack of other options (true need) was shown to make water recycling a reality; if the same holds true for P reuse, countries on the right side of the graph will be more eager to leverage recycled P in the near term. Countries in quadrants 1 and 2 currently practice considerable water reuse, generally on the basis of need (water stress) and largely to satisfy agricultural demands. This may lend itself to the fertigation business model, wherein total-value recovery is realized through agricultural water reuse leveraging nutrient value, while ideally extracting valuable energy and metals prior to effluent discharge. Alternately, nations in quadrant 4 lack substantial existing water reuse infrastructure and rely heavily on P imports; this means that they may want a concentrated form of recovered P to decrease the economic and political costs of P import. Thus, quadrant 4 may offer the greatest return on investment in P-separation infrastructure as part of total-value recovery, while quadrant 3 may experience slower rates of adoption due to lower P needs and less existing resource recovery infrastructure.

The type of P-recovery technology employed also influences the business model. As shown in Figure 4, crystallization processes applied to liquids from sludge dewatering (Group 1) are the commonly preferred option based on cost and energy considerations. Alternately, processes designed to recover P from ISSA (Group 2) are more expensive, but have much more favorable P-recovery capabilities. Options to recover P from sludge (Group 3) can extract similar amounts of P to those based on incineration, but additional energy demands and costs currently make them less attractive.[152] On the basis of energy and economic costs, P extraction from the liquid is most attractive, but considering the possible revenues from the fertilizer products and, in particular, the social and environmental benefits, several of these technologies may operate economically.[140] Comparisons among existing recovery modes in terms of feasibility, benefits, and opportunities for business development will vary based on priorities in different contexts.

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Environ. Sci. Technol. 2016, 50, 6606−6620

For example, process selections may differ between developed and developing countries based not only on technical sophistication and operational support, but also with respect to the allowable options for sludge use and growing awareness of environmental issues and demand for resource recovery.[153]

Currently, no business model can survive on the sale of recycled P materials alone. Most business models are hybrids with revenue streams consisting of (1) sales of technology/patent or operational service charges and (2) subsidies based on social benefits including cost offsets such as sustainable feedstock, process cost savings, and improved environmental quality and food security. In the case of Ostara, which is operational in Canada, the U.S., and Europe, the business model is founded on the service of P removal rather than the sale and actual reuse of the product.

Ostara's business model for struvite recovery is mutually beneficial for multiple parties.[147] The research and development partner benefits from the license fee on its patent. Ostara benefits from sale and/or operation of the recovery technology. Municipalities benefit from reduced operational costs associated with nuisance struvite precipitation, thereby allowing them to pay Ostara.[121] Additionally, the P removal helps treatment facilities meet their regulatory discharge permits. Yet, the recovered struvite is still more expensive than rock phosphate, and it represents a very small percentage of global P supplies, which has hindered current interest from the fertilizer industry. Thus, the wastewater-derived struvite recovered by most current technologies is marketed to high-end customers as premium-grade, niche-market P fertilizer, as there is a higher than usual willingness to pay in this scenario.

Financing for P-recovery technologies generally follows one of two strategies: (1) capital purchase model—the municipality or treatment plant operator pays for the installation, operates the facility, and recovers the costs through maintenance savings, often within a 3−10 year payback period, and (2) fee model—the business partner installs the P recovery unit using the build, operate, own model through a long-term contract. The fee model saves facilities the large upfront capital costs, and instead charges only a monthly fee, which should be below the facility's existing struvite-related treatment costs. Both models can involve a P-purchase agreement that allows the treatment plant to dispose of the unwanted struvite, and the P recovery company to market it.

4.3. Systems-Level Assessment Tools. Traditional design of wastewater treatment systems is based on function (sanitation and water quality), regulations, and cost. Broader social issues and environmental impacts across expanded geographic and temporal scales also are relevant, but difficult to quantify and compare with traditional metrics. To move toward total value recovery, the systems-level economic, environmental, and social considerations must be balanced. Typical economic analyses focus on the easily quantifiable/monetized costs and revenues. The next better approach is life cycle costing (LCC), which considers the economics over the life cycle of the product or process. Assessments using advanced economic analyses, such as LCC or techno-economic analysis (TEA), are needed to further address economic dimensions of sustainability.

Whereas economic analyses of P recovery from wastewater typically focus on internal costs, accounting for environmental and social benefits may make P removal and recovery more advantageous,[12] hence it is important to monetize these attributes. Doing so requires a broader range of social and ecological expertise than is typically devoted to engineering economic analysis. A range of systems-level assessment tools focused on the environmental facet of sustainability have been developed,[75,154,155] including life cycle assessment (LCA). LCA provides an established framework and methodology to evaluate the environmental costs and benefits over the life cycle of the product or process. An increasing number of LCA studies are focused on water and wastewater;[156] however, evaluations of treatment scenarios designed to recover materials while complying with increasingly stringent N and P removal requirements are scarce.[157,158] From LCA and energy-efficiency perspectives, recovery and reuse of nutrients is often more favorable in the environmental context than simply removing them during wastewater treatment.[33] Moreover, rock phosphate is likely to have a higher environmental burden compared to recovered P products when a system view is considered.[47] For example, urine source separation with P recovery as struvite had lower life cycle environmental impacts than P removal during wastewater treatment combined with synthetic fertilizer production, even when accounting for the new infrastructure required for urine source separation.[159] The advantage of systems-level analysis using LCA combined with LCC is that the trade-offs, for example, modification of existing (or requirement for new) infrastructure, can be assessed in terms of economic and environmental impacts.

To date, most of the published LCA-type research identifies the trade-offs between environmental and economic impacts. The next step is to incorporate social impacts. In general, the inclusion of social metrics in design and decision-making processes is a difficult undertaking.[12,24] Social benefits/costs (social equity) are associated with some economic impacts, and evaluations have often been limited to formal cost/benefit analyses. Other aspects of social motivation (to alter environmental behaviors) or impacts (especially with respect to equity) are now evaluated by surveys, focus groups, policy actor interviews, and other means. Several additional relevant methodologies (e.g., social LCA, risk assessment, and multicriteria decision support systems) continue to advance.[160,161] There is a need for future planning and design tools that account for social indicators such as equitable access to clean water and sanitation, public health protection, clear understanding and acceptance by all stakeholders, and equitable cost/impact apportionment and benefit accrual.[24]

While the water industry and environmental regulators have historically had insufficient data to consider the range of positive and negative trade-offs arising from advanced wastewater treatment scenarios,[158] assessments of each of the three dimensions of sustainability and evaluation of their relative trade-offs (e.g., using multicriteria decision analysis) will better inform future decisions.[24] Systems-level assessments will benefit from more standardized protocols and, in the future, should focus on trade-offs among technologies over different scales, public acceptance, and technology integration.[157] Systems-level analyses will evaluate impacts of P recovery strategies on water quality benefits and the array of value-added products, not just subsystem optimization.[162]

4.4. Regulations or Incentives. Most current P regulations focus on water body protection to mitigate eutrophication, whereas P recovery and reuse from waste are comparatively disregarded.[5] Many experts feel that policy measures (i.e., regulations, incentives) are needed to overcome current economic hurdles and help "kick start" P recovery and reuse.[46,163] Furthermore, policy measures are often the only

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Environ. Sci. Technol. 2016, 50, 6606−6620

recourse for avoiding negative externalities which are borne by future generations, for example, dissipation of concentrated P resources. Yet, today's governance structures do not explicitly address long-term P management.[4,25] Rather, P has primarily been managed as a pollutant based on its potential to cause eutrophication in freshwaters. Many regulations limit wastewater effluent discharges to approximately 1 mg-P/L.[109] However, increasing recognition of eutrophication risks in P-sensitive environments has reduced allowable levels to as low as 5−10 μg-P/L in some freshwaters.[103] Such regulations drive P removal from wastewater, often necessitating advanced treatment to achieve ultra-low concentrations. This could foster interest in P recovery, which may offset the extra costs of incremental reductions in effluent P concentrations (although the reverse could also be true depending on the type of technology implemented, i.e., Fe-based precipitation, which precludes recovery). Furthermore, hybrid removal/recovery systems that leverage the advantages of each approach could be implemented, wherein, for example, a P recovery technology could be used to recover 90% of the P, followed by removal of the remaining 10% to achieve ultra-low concentrations (strategies to achieve ultra-low removal are reviewed by Mayer et al. (2013)[103]).

Regulations on sewage sludge play a critical role in P recycling, with mixed implications for various recovered-P products. Land application is considered the most economical and beneficial sludge disposal method[164] and is encouraged in many regions. However, in some settings, use of sewage sludge is discouraged or limited due to heavy metals.[51] In other instances, N or P can limit agricultural application of sludge, which may encourage selective recovery of P from municipal or agricultural wastewater in order to reduce P content in the sludge,[12] thereby promoting recovery of multiple products.

P must be increasingly integrated into contemporary discussions on global environmental change and food security.[4,153] One step in that direction has occurred in Sweden, where the EPA established a national goal of recycling 60% of phosphate from wastewater by 2015 (including land application of biosolids).[153] Notably, Sweden's policies were defined in consultation among the Board of Agriculture, National Food Administration, National Chemicals Inspectorate, Institute for Infectious Disease Control, National Board of Health and Welfare, National Veterinary Institute, National Board for Consumer Policies, Federation of Swedish Farmers, Water and Wastewater Organization, Food Federation, and others, which illustrates the complexity of P recovery policy and its impacts on interrelated sectors.[162]

Energy policies may indirectly affect P recovery. For example, London's approach to reducing carbon emissions by 60% by 2025 includes a requirement that 20% of the city's energy comes from on-site renewable sources.[154] Waste-derived energy processes may play a role in this effort, and energy and nutrient recovery are natural partners, as described previously.[75] Moreover, while direct GHG emissions typically increase with more stringent N removal,[158] reductions in GHG emissions related to the Haber-Bosch process may provide a net benefit. Similar efforts to control carbon emissions, or encourage their sequestration can promote composting initiatives that reduce CH_4 production from landfills, and enhance soil carbon. Use of compost as part of a suite of recommended management practices can contribute to the sequestration of 50−1000 kg C/hectare/year.[165]

Eco-labeling may provide additional incentives for P recovery, as it could encourage trade and use of wastewater-derived products such as struvite if they were classified as recovered products rather than wastes.[51,166] To increase the competitiveness of these products and promote total value recovery, government subsidies, tax credits, and rebates, such as those supporting renewable energy products in the U.S., may be useful. Japan's subsidies for facility renovation encouraged recovery of HAP fertilizer at the Tottori and Senboku Wastewater Treatment Plants.

Economic constraints often limit municipal sewerage and wastewater treatment in developing countries. Thus, from the perspective of developing countries, national support mechanisms are needed for cost sharing, for example, a fair and equitable distribution of the costs of P recovery, financing of locale-specific innovations, and market adoption of existing technologies at scale. Moreover, for arid countries (including much of the developing world), water-based sewage transport may not be hydrologically sustainable. For these reasons, the developing world could leapfrog common 20th century sewage practices, perhaps incorporating N and P recycling early in the process, using techniques such as urine source separation.

4.5. Education. Public acceptance is pivotal for increased recovery of materials from "wastes." Acceptance hinges on education and demonstration projects showing that total value recovery from wastes can go hand-in-hand with public health and a more sustainable economy.[167] Demonstrating why resource recovery is needed and that it is safe will increase the likelihood of public acceptance.[99] Since 2008, a number of sustainable-P initiatives have been established, including, among others, the Sustainable Phosphorus Research Coordination Network (P-RCN), Phosphorus Recycling Promotion Council of Japan, Global TraPs (Transdisciplinary Processes for Sustainable Phosphorus Management), Global Phosphorus Research Initiative, and European Sustainable Phosphorus Platform.[168] These networks need to reach broader audiences by raising public awareness and acceptance about total value recovery. Universities and nongovernmental organizations must serve as sources of factual information and unbiased policy recommendations.[25,168] Moreover, establishing early and ongoing intensive communication among stakeholders (e.g., scientists and farmers) is essential, particularly given that some stakeholders may be skeptical of government-imposed policies.[169] As noted by Green et al. (2009),[170] "Dissemination [of knowledge] is not an end in itself; its intended benefits depend on integration and implementation by the end users, who will also determine the relevance and usability". Thus, end users must be considered early in the process[170] of realizing the total value of P recovery.

5.0. CONCLUSIONS

Although recovery and reuse of lost P for local or national food systems provide a double benefit of protecting environmental water quality and improving food security by minimizing supply risks, very little P recovery is practiced currently, largely due to unfavorable economics when P is the sole recovered product. The market value of the recovered P products alone is generally not high enough to justify the cost of recovery. However, when the total value of P recovery is considered, additional incentives emerge in support of P recovery. This total-value approach accounts for the P itself and the other products that can be simultaneously recovered, including renewable energy, N, minerals and metals, and water. A natural coupling with

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Environ. Sci. Technol. 2016, 50, 6606−6620

pathways for P recovery emerges in many of these recovery scenarios.[26] Additionally, P recovery provides a number of services that are not easily monetized, but which are quite important to society and the environment. These include protecting and improving water quality, improving operation and performance at waste treatment facilities, and improving food security and social equity.

To make P recovery a reality, successful business models are needed to turn the various values of P recovery into commercial success, technology bottlenecks must be overcome using innovative approaches to corecover products, and policy and education strategies must be implemented to make P recovery socially acceptable. To substantially satisfy P demands, recovery should be practiced at a variety of scales (e.g., developing and developed countries) using P sourced from a variety of flows (e.g., animal, municipal, and industrial wastewater; environmental waters and agricultural runoff; organic and industrial waste).

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.6b01239.

The statistical analysis of correlation of water reuse to water risk, economics, human development index, and education (PDF)

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Notes

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