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Nitrogen and Phosphorus Recovery from Anthropogenic Liquid Waste Streams

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Abstract

Nutrient recovery from waste is a promising strategy to conserve inputs while reducing nutrient discharge to the natural environment. Multiple waste streams have shown promise with respect to nutrient recovery. Multiple technologies also show promise at a pilot or full scale. These technologies, however, must not exacerbate other environmental issues, with excessive energy use, unsustainable material extraction (e.g., mineral extraction, cement use), or toxin release into the environment. Such technologies must also be feasible from economic and social perspectives. Work, therefore, should focus on both improving our current suite of available technologies for nutrient recovery from waste and framing policies that blend affordability with incentives, thereby fostering an environment conducive to innovation and adoption of sustainable approaches. This review considers the issues associated with nutrient recovery from waste, including technical feasibility and economic, environmental, and social factors, and identifies current knowledge gaps and emerging opportunities for nutrient waste recovery.

Contents

1. INTRODUCTION: NUTRIENT RECOVERY FROM WASTE STREAMS

Macronutrients, including nitrogen and phosphorus, are critical resources for agricultural, municipal, and industrial systems. Nitrogen supports all life forms, including crops and livestock that feed the growing human population. Reactive nitrogen is created using the Haber–Bosch process (120 TgN/year globally), enabling nitrogen fixation at a rate higher than microbiological nitrogen fixation (63 TgN/year globally) (1). The majority of fixed nitrogen is applied as fertilizer (98 TgN/year globally) (2), with the remainder used for other industrial applications such as the production of explosives. Phosphorus also supports life and is a resource that is, today, unsustainably extracted from apatite minerals that have an estimated reserve of 50–150 years (3). The global rate of extraction is approximately 20 TgP/year, which is the major source of phosphorus for fertilizer production (4).

As anthropogenic nutrients enter the natural nitrogen and phosphorus cycles, loss from the biosphere occurs through physical and biological processes, such as leaching, runoff, volatilization, and denitrification. Inefficient utilization of these nutrients leads not only to waste of valuable resources but also to pollution, such as eutrophication, resulting in negative environmental, economic, and social impacts. Both inland and coastal aquatic ecosystems and communities can be negatively affected by eutrophication, which poses threats to water resources and biodiversity as well as to fishing and tourism (5). Currently, the global rate of anthropogenic nitrogen influx of 120 TgN/year is significantly exceeding the proposed safe planetary boundary of 35 Tg/year (6, 7). As a result, there is an urgent need to limit the anthropogenic extraction of reactive nitrogen and phosphorus from the geosphere and to reduce the release of anthropogenic nutrient waste streams into natural ecosystems.

Nutrient recovery: recovering nutrients from waste

Nutrient recovery from waste is a promising strategy that can address potential shortages or a lack of access to nutrients. Nutrient recovery also reduces nutrient discharge to the natural environment. The waste nutrients in municipal wastewater alone can meet 20% and 15% of current fertilizer demand for nitrogen and phosphorus, respectively (8, 9). Replacing fertilizers with recovered nutrients can offset the energy demand and costs of anthropogenic nitrogen fixation (10 kWh/kgN) and phosphate mining (0.02 kWh/kgP) (10, 11). Incorporating nutrient recovery strategies into wastewater treatment can also reduce sludge production and undesirable precipitation, thereby lowering the environmental impact and cost associated with sludge processing and piping maintenance (12). Commercialization and widespread application of nutrient recovery from waste are currently limited, however, with emerging nutrient recovery technologies encountering technological, economic, and social hurdles (10). Different technologies produce distinctively different recovered products for downstream applications, and the technological, economic, and social hurdles vary significantly, depending on the targeted waste stream (13).

This review considers the issues associated with nutrient recovery from waste, identifies current knowledge gaps, and discusses emerging opportunities for nutrient waste recovery. We outline the benefits and drawbacks of nutrient recovery from major waste streams, detailing their capacity, ease of collection, distribution, and associated environmental and socioeconomic issues. We also review nutrient recovery technologies tested at a pilot scale or beyond. Finally, we explore the challenges of nutrient recovery, emphasizing the need for sustainability through addressing environmental, economic, and social factors, including energy demands, scalability, operational capacity, and the logistics of consolidating diverse waste streams for efficient recovery.

2. POTENTIAL FOR AND LIMITATIONS OF NUTRIENT RECOVERY FROM MAJOR NUTRIENT-CONTAINING WASTE STREAMS

The feasibility of nutrient recovery depends on critical factors, including the concentration of nutrients in the waste, the quantity of the waste streams available, the consistency of the waste stream, colocation with nutrient demand, collection infrastructure, and the occurrence of cocontaminants (**Figure 1**). Furthermore, nutrient-rich waste streams can be categorized as point source or non–point source. Point source waste streams are released from specific sites and include municipal wastewater, industrial wastewater, and landfill leachate. Non–point source waste streams are diffuse or associated with multiple locations and include agricultural wastewater and urban runoff. The characteristics, collection, and treatment of point source versus non–point source waste streams are very different. The maximum amount of nutrients that can be recovered from a waste stream depends on its total available volume and the concentration ranges of nitrogen and phosphorus that are present. Collection, storage, and transportation needs also depend on whether the waste is generated from point source or non–point source waste streams, the location and time they are generated, and the location of end users for the recovered nutrients (14). Colocated nutrient supply and demand encourage local recovery and reuse, whereas dislocated nutrient supply and demand necessitate concentration and transportation of recovered nutrients and/or waste streams, requiring that specific technologies, infrastructure, and/or policies be applied. Variability in the quality and quantity of nutrients over time may necessitate equalization and storage facilities for continuous treatment and recovery processes. Moreover, the co-occurrence of other contaminants within nutrient waste streams, such as emerging organic contaminants, heavy metals, and pathogens, may limit the ability to use recovered nutrients (13).

2.1. Non–Point Sources

This section discusses two major nutrient waste streams from non–point sources, including runoff from agricultural and urban land use areas.

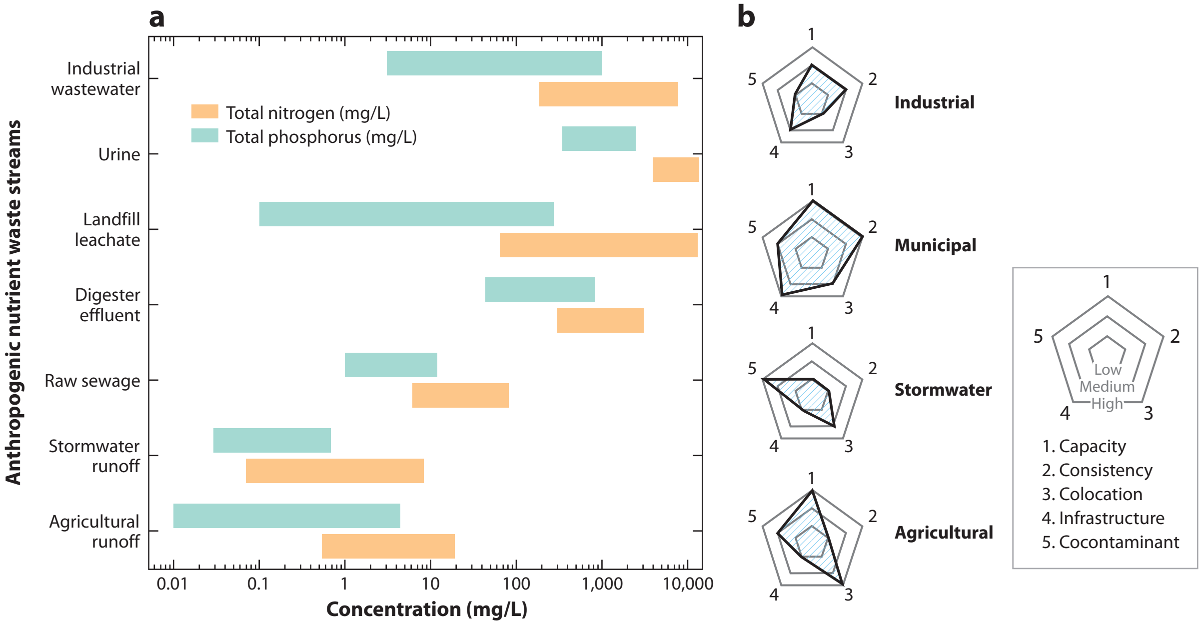

Figure 1

(*a*) Nitrogen and phosphorus concentrations of waste streams. Concentrations on the *x* axis are on a log scale. (*b*) Each waste stream was graphed with respect to its capacity, consistency, colocation with demand, existing infrastructure, and cocontaminant load. The three radial lines represent levels of low, medium, and high with respect to nutrient recovery capacity, consistency of nutrient loading, colocation with nutrient demand, need of new infrastructure, and exclusion of cocontaminants. A larger shaded area indicates a preferred waste stream for nutrient recovery overall.

2.1.1. Agricultural runoff.

Approximately 70% of annual freshwater withdrawals by human society are used for irrigation (15). When combined with precipitation, this generates a waste stream that carries away excess nutrients from agricultural fields (**Figure 2**). Agricultural runoff is difficult to monitor, collect, and utilize. The total global nitrogen input to agriculture, including fertilizer application, manure, and natural nitrogen fixation and deposition, was estimated in 2000 to be 248 Tg/year (16). Although a great deal of that nitrogen is taken up by crops or lost through ammonia volatilization or denitrification, approximately 57 Tg/year residual nitrogen ends up in drainage or runoff from agricultural sites. Likewise, the total global phosphorus input to agriculture was approximately 31 Tg/year in 2000, with approximately 4 Tg/year lost in drainage or runoff (16). The majority of the nitrogen present in runoff is dissolved as nitrate, while phosphorus is mainly bound to soil and particles, with reported concentrations of total nitrogen (TN) of 0.5–20 mg/L and total phosphorus (TP) of 0.01–4.5 mg/L, respectively (17).

Land use management affects the nutrient concentrations in runoff, with higher concentrations often associated with horticulture, dryland cropping, and grazing activities (18). Collection, storage, and/or treatment infrastructure is rarely present, even though agricultural runoff is generated at locations with nutrient demand. Instead, the main drivers for agricultural wastewater reuse are water scarcity and discharge regulations. Nutrient management strategies today most commonly are limited to the reduction of fertilizer overdoses, removal along the runoff pathway, and catchment/treatment prior to discharge (19). Common co-occurring contaminants with nutrients in agricultural runoff include pesticides, pathogens, heavy metals, and salts. High total dissolved solids and toxic elements, such as selenium and boron, are also frequently encountered, and advanced treatment is generally required for reuse to become an option (20).

TN: total nitrogen

TP: total phosphorus

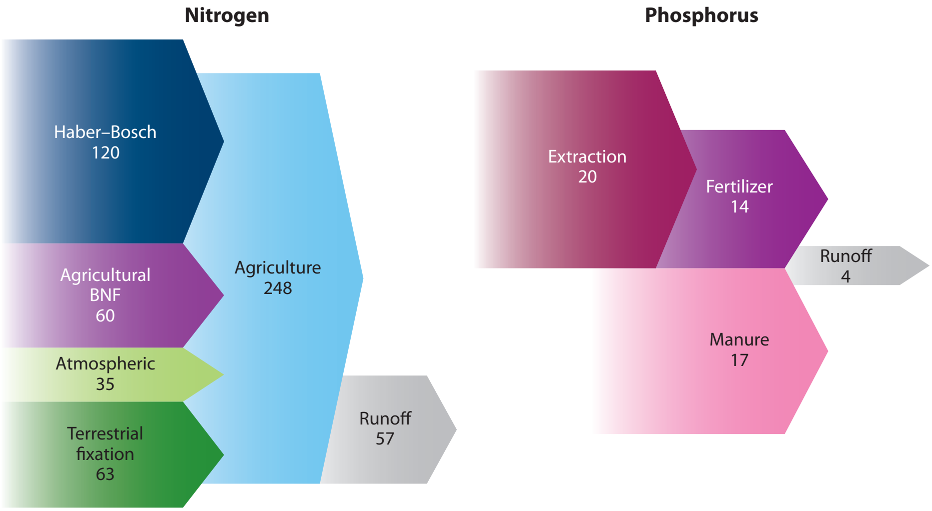

Figure 2

Loss of nitrogen and phosphorus from agricultural activities. Nitrogen is sourced from anthropogenic fixation (the Haber–Bosch process), agricultural biological nitrogen fixation (BNF), atmospheric deposition, and terrestrial fixation of nitrogen. Phosphorus is sourced from extraction of phosphate mines and biological phosphorus. The numbers are estimated global rates in teragrams per year. Data are from References 1, 4, and 16.

2.1.2. Urban runoff. Nutrients in urban runoff are carried away by stormwater and originate mostly from atmospheric deposition, construction, lawn fertilizer, pet waste, and unsewered development (21). Untreated excreta from humans and pets can be a significant source of urban nutrient runoff in regions with leaking sewage systems and high pet ownership rates. For example, pet waste contributed up to 70% of TP in the urban runoff of Saint Paul, Minnesota (22). Notably, this is a fraction of a diluted waste stream. In Minneapolis, Minnesota, the average stormwater runoff concentrations of TN and TP were 3 mg/L and 0.6 mg/L, respectively (23).

Urban runoff increases with urbanization, as impervious surfaces expand. Patterns of land use and the connectivity of impervious surfaces can also affect the volume and composition of urban runoff (24). The volume of urban runoff is highly variable and is strongly influenced by climate conditions. For instance, runoff volumes can range from 24 to 28,000 m^3/event, based on rainfall amount, watershed area, and percent impervious area (23). Seasonal and extreme weather events such as snowmelts and stormwater also contribute to the temporal variations in runoff volume and nutrient concentrations. Nutrient loads can thus be correlated with rainfall intensity, surface flow connectivity, and entrained sediments associated with phosphorus (24). Nevertheless, urban runoff is generally low in nutrient concentrations. According to a survey conducted by the US National Pollution Discharge Elimination System Stormwater Program, median TN concentrations were mostly below 3 mg/L, and nitrogen was not perceived to be an important pollutant of concern (25).

In addition to source control and public education, engineered structures have been used to attenuate and retain nutrients before release to stormwater (24). For example, a combination of stormwater detention basins and best management practices has been shown to be effective in retaining phosphorus in soil (26), minimizing its flux into runoff. Nutrients are also assimilated by vegetation in best management practices such as bioretention cells, grass swales, wetlands, and green roofs (24). These are efficient ways of colocalizing nutrient recovery and reuse from stormwater while also improving the urban landscape. While there is no existing infrastructure for recovering nutrients from urban runoff, co-occurring contaminants such as solids (trash and sediments), oil and grease, heavy metals, pesticides, pathogens, and trace organic contaminants add significant obstacles for reuse (26, 27). As a result, the fate and transport of cocontaminants, along with their toxicity and potential synergistic effects on human and aquatic health, need to be monitored if the waste stream is to be diverted for nutrient recovery, especially when recovered nutrients are utilized for agriculture.

CECs: contaminants of emerging concern

2.2. Point Sources

Unlike non–point sources, nutrients are discharged from identifiable sources such as municipal and industrial wastewater and landfill leachate.

2.2.1. Municipal wastewater. Approximately 380 billion m^3/year of municipal wastewater is generated worldwide at an (world) average of 95 m^3 per capita per year (28). The amount of wastewater produced per capita varies significantly with water scarcity, land use, and other social and economic factors. For example, high-income countries produce 41% of global wastewater, despite having only approximately 16% of the global population (29). Municipal wastewater flow rates and water quality exhibit temporal and seasonal variability depending on water usage and weather conditions (30). Extreme anthropogenic and natural events, such as floods, droughts, and industrial pollution, also affect nutrient concentrations in wastewater.

The average nutrient concentrations of medium-strength wastewater surveyed across various locations worldwide are 44 mgN/L and 8 mgP/L (28). Wastewater consists mainly of human excreta diluted with flush water and gray water from kitchen, shower, and laundry activities. Therefore, variations in concentration can be attributed to regional differences in dietary habits, incomes, and water-saving measures. For example, the excessive consumption of protein in the United States has led to an increase in nitrogen loading to downstream environments (31). Urine, contributing typically less than 1% of the wastewater volume, contributes approximately 80% of wastewater nitrogen and 56% of wastewater phosphorus (32). A median volume of 1.4 L urine per capita per day is excreted (33). As a concentrated waste stream of nutrients, urine also has a nitrogen-to-phosphorus ratio similar to that demanded by crops, making it an attractive nutrient source for recovery if urine separation is possible. Within a wastewater treatment plant, a sidestream containing high concentrations of nutrients can also be generated if anaerobic digestion processes are in place. As organic carbon is degraded to volatile methane and carbon dioxide during digestion, a nutrient-rich sidestream remains and can be treated for nutrient recovery.

Colocation of nutrient demand and municipal wastewater varies greatly with the geological distribution of population and land use within various countries. For instance, nitrogen supply from urine is colocated with agricultural demand in most parts of China, India, Uganda, and Nigeria, whereas most of the supply and demand are dislocated in the United States and Brazil (14). Islands and coastal regions often have dislocated nutrient supply and demand, requiring additional efforts for nutrient transport to areas of need/application (14). An alternative to the transportation and relocation of recovered nutrients to distant agricultural regions is scaling up urban agriculture. Such colocation can increase energy efficiency and offset the environmental impacts of waste nutrients and carbon dioxide (34).

Even if other factors (such as infrastructure and colocation) are managed, studies have raised concerns about the accumulation and dissipation of antibiotics/antibiotic resistance genes with the use of treated wastewater for irrigation and the use of biosolids as fertilizer (35). Additional contaminants of emerging concern (CECs), including pharmaceuticals, personal care products, and flame retardants, can also be present in the nutrients recovered from wastewater (36). The fate and transport of CECs, antibiotics, and antibiotic resistance genes during nutrient recovery from municipal wastewater need to be carefully considered to ensure the health of humans and the ecosystem receiving these products.

Resource recovery: recovering useful materials from waste

2.2.2. Industrial wastewater.

Food processing and agricultural industries such as animal husbandry operations, dairy plants, beverage plants, and slaughterhouses also produce nutrient-rich waste streams. Meat and dairy processing consume approximately 36% of the water of the entire food and beverage industry in the United States (20). These industrial waste streams are regionally variable, however, with washing wastewater from dairy farms varying from 12–20 L/cow-day in the Netherlands to 100–200 L/cow-day in the United States (37). In addition, different animals produce different waste streams, with dairy manure typically low in phosphorus and poultry waste high in phosphorus. Similar to municipal wastewater, anaerobic digestion of these waste streams produces a nutrient-rich digestate that can be used for resource recovery (38).

Some non-food-related industries such as leather tanning, coal-based power plants, semiconductor manufacturers, and steel plants also generate high-concentration nutrient wastes; however, such wastewaters often lack a balanced proportion of nutrients. For example, cola beverage waste contains only phosphorus, whereas coking wastewater contains high ammonia (39).

Industrial wastewater flows often follow diurnal cycles or work week and holiday shift schedules, resulting in a need for tanks or holding ponds to facilitate nutrient recovery from these wastewaters. While storage tanks are needed for animal waste slurries and other agricultural/farm wastes to prevent direct discharge to soil/surface water bodies (37), wastewater generated from an industrial facility, such as that from dairies, can be collectively discharged into the municipal sewer, depending on waste characteristics and local environmental regulations. Although locations of such facilities do not necessarily overlap with locations of high nutrient demand, cooperative arrangements between different industries located in close proximity to each other can be developed to combine, treat, and transport recovered products from their nitrogen- and phosphorus-rich wastewaters, which can also balance variable flows and nutrient concentrations (39, 40). The direct use of wastewater from agricultural point sources can harm public health and local ecosystems by potentially spreading CECs and antibiotic resistance genes (40); additionally, certain industrial wastewaters like coking wastewater demonstrate significant phytotoxicity, necessitating advanced oxidation processes to eliminate stubborn and toxic organic substances before the wastewater can be utilized (41).

2.2.3. Landfill leachate.

Leachates originate from landfilled materials and aqueous streams, including precipitation, surface drainage, and groundwater, entering the landfill. Depending on the method of refuse compaction and percolating conditions, the flow rates of leachate can range from 15% to 50% of the local annual precipitation, with large variations over time (0–24 m^3/day) (42). The composition of leachate also varies with waste type, soil condition, and landfill age. Landfills go through a sequential process of maturation, with aerobic decomposition occurring within a month, hydrolysis and fermentation taking place for a few years, and anaerobic methanogenesis continuing after that (43). Leachate is often lean in phosphorus, with concentrations less than 50 mg/L, which can limit biological degradability (44). Ammonia and TN concentrations in leachates remain relatively high and stable during maturation, ranging from 500 to 4,000 mgN/L (45). Indeed, there are 100–210 Bt of ammonia from leachate treatment plants annually that could meet 4–5% of the global fertilizer demand if captured (4). Co-occurring contaminants of concern in leachate are mainly heavy metals and xenobiotic organic compounds (45). Infrastructure exists in industrialized countries to collect and drain the leachate from a landfill, enabling downstream nutrient recovery (46).

3. RECENT ADVANCES IN AND CHALLENGES OF NUTRIENT RECOVERY TECHNOLOGIES

TRL: technological readiness level

There has been a great deal of interest in the recovery of nitrogen and phosphorus from waste, with a concomitant focus on developing viable and scalable technologies to accomplish such recovery (**Table 1**). Here we focus on nutrient recovery technologies that have been successfully demonstrated at a pilot scale [technological readiness level (TRL) 5–6] or at full scale (TRL 7–9). In general, these technological approaches fall into categories of either nitrogen/phosphorus concentration or nitrogen/phosphorus separation/purification, with some waste streams and final applications requiring both while others, depending on the end use of the recovered nutrient and/or the waste stream used, require only one or the other (**Figure 3**). Likewise, some technologies such as membrane-based technologies can perform either concentration or separation/purification, depending on the feed stream, the technological parameters (e.g., type of membrane used), and the operational strategy.

3.1. Technological Considerations

When one is weighing which technologies are best suited to a given application, critical considerations include (*a*) the feed concentration at which a technology performs best, (*b*) the ability to scale the technology to an expected capacity (i.e., TRL, ease of scalability), (*c*) the ability of a technology to manage waste streams of different flow consistency or intermittency, (*d*) the existence of the needed infrastructure to enable a technology to function properly, (*e*) the ability of the final product to either be colocated with demand (i.e., technology easily operated in a distributed manner) or be efficiently transported to the site of use, and (*f*) the ability of a technology to manage the presence of cocontaminants and create a product of sufficient safety (e.g., lack of pathogens or heavy metals) and purity for its intended use. Below we consider different technologies (**Table 1**), including physical and chemical, membrane, electrical, and biological processes, through the perspectives of these critical considerations.

With respect to commonly applied physical and chemical treatment processes, including ion exchange, precipitation, and stripping, all of these treatment processes have been successfully applied at a pilot or full scale with feed streams of urine or digester supernatant. Similarly, biological treatment systems, including enhanced biological phosphorus removal (for phosphorus) and algal technologies (for nitrogen plus phosphorus concentration) have been demonstrated and applied at a pilot or full scale. Other treatment processes, such as membrane technologies and electrochemical technologies, either are somewhat less proven or face technical challenges in scale-up. Below we discuss each of these treatment process categories, including their niches, limitations, and benefits.

3.2. Physical and Chemical Treatment Processes

Nutrients can be concentrated or extracted from liquid waste streams through physical and chemical processes, including adsorption onto solid surfaces, precipitation of solids, and stripping of gases. Other common treatment techniques, such as electrochemical processes and membrane-based processes, are also discussed in this section.

3.2.1. Ion exchange. While ion exchange has been used for nitrogen and phosphorus recovery (103), evidence for successful long-term demonstration at a pilot scale or greater for phosphorus recovery is limited (104, 105). The process is typically used as a purification/separation step after initial concentration and pretreatment of medium-strength feed streams such as digestate. Ion exchange material adsorbs/exchanges ammonium for a counterion, resulting in concentration

Table 1 Current nutrient recovery technologies

Technology	Demonstrated waste stream	Recovery efficiency	Working range of concentration	Recovered end product	Operational cost	Environmental impacts	Limitations and challenges
Physical and chemical							
Ion exchange	Urine (47, 48) Municipal wastewater (49, 50)	Resin: Dowex Mac 3, 56 mgN/g with urine (51) Layne^{RT}, 41 mgP/g with wastewater (50) Zeolite: Clinoptilolite, 15 mgN/g with urine (52) Chabazite/Phillipsite, 33 mgN/g, 78–91% with wastewater (49) Biochar: 48 mgN/g, 116 mgP/g with urine (48)	100–500 mgN/L (52) <200 mgP/L (48)	Absorbed ammonium	£2.35/kgN with hybrid ion exchange resin (53) $6/kgN with 100 regenerations of resin (54)	Major contributor to energy consumption and greenhouse gas emissions in the regeneration process (55) Reduction in transportation-related emissions relative to untreated urine	Low solid content (<2g/L) Chemical scaling and biofouling Salt requirement for regeneration (56) Completing ions for adsorption capacity
Precipitation	Urine (57–59) Phosphating wastewater (60) Anaerobic digestate (61) Refuse leachate (62)	P: MgO/seawater, >87% with urine (57) $MgCl_2$: 85–99% with urine (59, 63) Biochar: 96% with leachate (62) N: MgO, 80% with urine and clinoptilolite addition (58)	100–500 mgP/L with urine (63, 64) 30–150 mgP/L with digestate (61)	Struvite, with montgomeryite, newberyite, brucite, and epsomite	AUD$0.16/kgP with wastewater (65) $1.9/kgP with zinc coprecipitation (60) Operating expenses can be completely covered by struvite sale (61)	Low residual heavy metal and pharmaceuticals in recovered struvite (63, 64) Manufacturing of synthetic Mg chemicals (66)	Fouling may be minimized by providing struvite seed for nucleation (57)
Stripping	Urine (64) Anaerobic digestate (67) Landfill leachate (68) Industrial wastewater (69)	85% with urine (64) 65–76% with digestate (67) 74–90% with vacuum steam stripping and leachate (68)	1,600–6,200 mgN/L with urine (64) 2,900–3,600 mgN/L with leachate (68)	Concentrated ammonia solution	€3–6/kgN with digestate (67) £4.4–4.8/kgN with digestate (70)	CO_2 prestripping can reduce alkaline dosage Sustainable alternative to sulfuric and nitric acid as scrubbing agents	Energy intensive (71) More efficient reactor designs are needed (69)
Membrane based							
FO	Urine (72) Anaerobic digestate (73) Wastewater (74)	>90% P and 50–86% N with urine (72) 98% P and 73–76% N with digestate	3,400–4,300 mgN/L with urine (72) 780 mgN/L and 220 mgP/L with digestate (73) 37 mgN/L and 3 mgP/L with wastewater (74)	Concentrated ammonium solution, struvite	$0.64/kgN with $MgSO_4$ (72) $0.29/m^3 wastewater with FO-LPRO (75)	Potential of freshwater recovery Partial rejection of micropollutants (76)	Reduced cost of Mg salt for draw solutions needed Selective membrane needed to improve ammonia rejection Membrane biofouling

(*Continued*)

Table 1 ***(Continued)***

Technology	Demonstrated waste stream	Recovery efficiency	Working range of concentration	Recovered end product	Operational cost	Environmental impacts	Limitations and challenges
Membrane based							
Nano/microfiltration	Anaerobic digestate (77, 78) Wastewater (79)	69% N with digestate (78) >90% P with digestate (77)	700 mgN/L and 40 mgP/L (78)	Permeate	£1.3–£3.3/kgN (37) €0.06/m^3 with coagulant (79)	Simultaneous K recovery is possible Pathogenicity of permeate	Cake formation on membrane surfaces Residual ammonia Increased cost with acidification (78)
Membrane contactor	Digestate (80) Industrial wastewater (81) Landfill leachate (82)	73–95% N with hollow fiber membrane (81)	700–3,400 mgN/L in digestate (80) 500–5,000 mgN/L in industrial wastewater (81)	Ammonium sulfate solution	\$5.11/kgN with solar energy (82) €0.6/kgN at full-scale WWTP (83)	Reducing N_2O and CO_2 emission in WWTP (83) Fugitive NH_3 emission (84) Production of membrane and acid	Membrane fouling and cleaning in place Osmotic distillation that floods/empties the strip solution vessel (85)
Electrochemical							
ED	Urine (86, 87) Digestate (88)	80–88% N with bipolar ED (86) 20–26% N (88) 31% N with microbial electrolysis (87)	800–4,000 mgN/L in urine (86, 87) 460–1,200 mgN/L in digestate (88)	Concentrated N and P solution	Majority is electricity consumption \$5.22/m^3 digestate (89)	Fugitive NH_3 emission (88) Additional burdens from electrode and membrane replacement	Current efficiency needs improvement, and ionic shortcuts need to be prevented (86) Membrane fouling and cleaning Bioanode stability and oxygen in catholyte (87)
Electrochemical precipitation	Wastewater (90) Urine (91) Swine wastewater (92) Digestate (93)	80% P as hydroxyapatite (90) 99% P and 90% N as struvite (92) 97% P and 89% N with stripping (94)	180 mgN/L and 19 mgP/L (90)	Hydroxyapatite, struvite, vivianite	\$3.87/m^3 digestate (93)	Avoided alkaline addition Acidic solution can be used for cleaning High pH can stabilize urine (91)	Adsorption of organics on ion exchange membrane (94) Salt accumulation Collection of precipitation
Biological							
Algal	Wastewater (95) Digestate (96)	30–40% N and 70–80% P (95)	150–250 mgN/L (95, 96) 5–35 mgP/L (96)	Algal biomass	€4.3/kgN with raceway pond (96)	CO_2 fixation by photosynthesis Biostimulants to crops (97)	Pathogen contamination Inhibition with high N and solids (98) CO_2 addition required for efficient treatment
EBPR	Wastewater (99, 100)	75% P as biosolids and struvite (99)	30–50 mgN/L and 3–7 mgP/L (100)	P-rich biomass	€6–38/kgP from sludge, depending on recovery technology (101)	Low environmental impacts of biological process Additional infrastructure may be required	Sensitive to inhibitors (102) Downstream sludge processing or P extraction is required

Abbreviations: EBPR, enhanced biological phosphorus removal; ED, electrodialysis; FO, forward osmosis; LPRO, low-pressure reverse osmosis; WWTP, wastewater treatment plant.

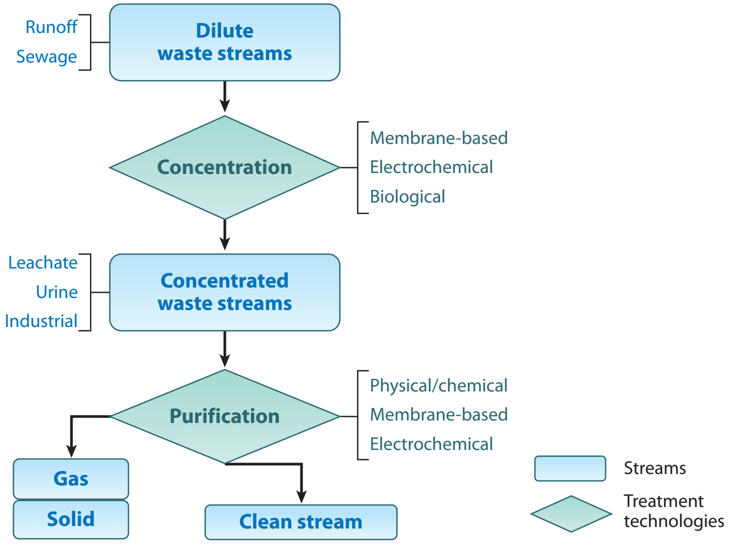

Figure 3

General schematic of the usage of concentration technologies and separation/purification technologies for nitrogen and phosphorus recovery from wastes.

of the nitrogen on the exchanger surface while simultaneously changing the waste stream chemistry through the release of the counterion. Once the nitrogen is exchanged onto a sorbent, the sorbent itself can be used, for example, as an agricultural amendment (106), or more typically, the nitrogen can be desorbed from the sorbent and used directly or subsequently purified further (e.g., via precipitation). Desorption increases the chemicals needed for nitrogen recovery via ion exchange (107) but allows the exchanger itself to be reused. A variety of ion exchange resins or sorbents, including natural materials such as zeolites (e.g., clinoptilolite) and biochar, as well as synthetic resin sorbents, have been shown to be effective for nitrogen recovery from urine (54). Although pretreatment of urine prior to ion exchange does not appear to be needed, source separation and urine storage/collection are required, highlighting the infrastructure requirements for any treatment process using urine as a feedstock.

In general, feed streams need to be low in solids to prevent the clogging of exchanger media. Precipitation of nitrogen and/or phosphorus [for example, as struvite ($NH_4MgPO_4 \cdot 6H_2O$)] can occur at the surface of sorbents (62), generating particulates in the system. The use of ion exchange sorbents for the removal of (dilute) ammonium from wastewater has not yet been shown to be effective at scale (56, 108, 109), requiring a sorbent that is highly selective and that does not foul. Nevertheless, different configurations and operational parameters have been studied for such applications, with recommendations for future pilot testing (47).

Ion exchange is a flexible technological choice for nitrogen recovery. This technique functions effectively at a range of concentrations (52), works well with intermittent flows (47), generates a product that can be easily transported (106), and is able to create a product, through precipitation, with minimum accumulation of trace organic contaminants (47). Nevertheless, it has not been shown to function well for nutrient recovery from municipal wastewater, which contains lower concentrations of nitrogen and phosphorus along with high concentrations of other anions, cations, and organic carbon, making the exchangers subject to biofouling and chemical scaling. Added to this limitation is the requirement of chemical addition (acid or salt) for the regeneration of the sorbent. The development of more selective, reusable, and inexpensive resins for nitrogen and phosphorus recovery from complex and dilute mixtures, such as wastewater, will be required for ion exchange to become effective for nutrient recovery at scale (56). While urine is the most studied waste stream for nutrient recovery through ion exchange, significant infrastructure advances and improvements are needed to scale up urine separation and collection strategies.

3.2.2. Precipitation. Struvite precipitation is a proven method of nitrogen and phosphorus recovery from urine and digester supernatant, with the capability of recovering 85–99% of the nitrogen and phosphorus present in the feed stream (61, 110). Nevertheless, as the stoichiometry of struvite is not consistent with the nutrient makeup of most waste streams of interest, the recovery of nitrogen often requires phosphorus and magnesium to be added to the waste stream (111), whereas the recovery of phosphorus requires that magnesium be added [at a ratio of 1.1:1 Mg:P (112)], with excess nitrogen often remaining in the resulting effluent. The form of the added magnesium also impacts phosphorus precipitation as struvite (112), requiring appropriate magnesium sourcing to achieve the greatest phosphorus recovery. Because of the complexity of struvite stoichiometry, struvite precipitation is often a first step in nutrient recovery, followed by the application of additional nitrogen recovery (or treatment) methods, such as adsorption/ion exchange, stripping, and membrane concentration. Alternatives to struvite for phosphorus recovery, such as hydroxyapatite (113) and vivanite (114), have also been studied.

Precipitation is an excellent technological choice for phosphorus recovery and a flexible choice for nitrogen recovery, at least as an initial step. Precipitation is thermodynamically favored at high nutrient concentrations (63); therefore, precipitation requires the use of either a concentrated waste stream or an initial concentration step prior to application. Precipitation is a simple, scalable technology that has been proven at full scale, works well both in batch mode (60) or with continuous flows (115), and generates a clean product with commercial value (110). Precipitation is therefore a key strategy for nutrient recovery, and as with ion exchange, if infrastructure were added to support urine separation and collection, the application of precipitation for nitrogen recovery would expand. Limitations of precipitation are the need for a sustainable source of magnesium, particularly in large-scale operations, and cocontaminants. For example, insufficient inactivation of pathogens during precipitation processes (116) requires additional posttreatment steps.

3.2.3. Stripping. When nitrogen is present as either NH_3 or NH_4^+, stripping is an effective way to recover nitrogen from concentrated waste streams, utilizing the pH-dependent equilibrium between ammonium and ammonia gas to force nitrogen into the gaseous phase for collection/recovery. It is a fast and effective final step for nitrogen recovery, with a relatively small footprint for stripping towers. The stripping process is efficient only when applied to waste streams with very high concentrations of ammonium, such as urine and some industrial wastewaters. Dilute waste streams require a concentration step before stripping can be used to recover nitrogen. Ammonia stripping functions well regardless of cocontaminants (e.g., organic carbon) in the waste stream, although pretreatment can reduce operational cost. For example, CO_2 prestripping was used to reduce base requirements for pH adjustment up to 60% (67). Pretreatment for calcium and magnesium removal can also reduce fouling during stripping. Thermal vacuum stripping can increase ammonia recovery and reduce heating requirements under negative pressure. This technology has been demonstrated with anaerobic digestate (117) and landfill leachate (68).

Stripping can recover up to 99% of the nitrogen in waste as ammonia gas (112). The subsequent use of the stripped ammonia requires further processing, typically via the capture of ammonium in an acidic solution. With respect to ammonium capture, the most commonly used scrubbing agent is sulfuric acid; researchers are, however, exploring more sustainable and safer alternatives, such as citric acid and acetic acid (118). Intensive energy consumption is another barrier to the application of ammonia stripping, with reports of electricity consumption of up to 7 kWh/m^3 (71). Future research is needed to improve reactor design and stripping efficiency and to enhance the sustainability of pH adjustment methods and ammonia capture with absorption.

3.3. Membrane Processes

Membrane-based technologies use semipermeable ceramic or polymeric films to mechanically separate nutrients from their matrices; the process can be driven by external pressure, concentration or temperature gradients, or electrical potential. Various technologies, including forward osmosis (FO), nano- and microfiltration, and membrane contactors, can be used with a wide range of feed stream concentrations and are suitable for the concentration of dilute waste streams or the purification of nutrients within a more concentrated waste stream.

FO uses a membrane to separate a concentrated draw solution that pulls water molecules across the membrane, leaving behind a concentrated solution. FO has been demonstrated to concentrate both urine (72) and wastewater (74), only requiring a draw solution with a higher osmotic pressure for operation. FO systems are generally less efficient at ammonia rejection than phosphorus rejection, due to the bidirectional diffusion of ammonium (119). Nevertheless, when magnesium salt–containing draw solutions are used, an increase in the pH during operation can promote the precipitation of struvite in the concentrated feed solution (73), achieving simultaneous nitrogen and phosphorus recovery. Hybrid systems with combined membrane and physical and chemical processes can be used to regenerate draw solutions in FO while recovering additional nutrients and resources from waste streams. For example, reverse osmosis can be used to harvest freshwater from the draw solution, with membrane distillation used to recover ammonia (120).

Nano- and microfiltration are pressure-driven processes that push certain compounds through a semipermeable membrane into a permeate stream while retaining additional compounds in the concentrated retentate. These processes are suitable for the purification of nutrients from solid-containing waste streams. With acidification, membranes can effectively concentrate phosphorus in the permeate using both size- and ion-selective filtration (121), leaving other contaminants, including multivalent heavy metals, in the retentate. Membrane selectivity for monovalent ions is not perfect, allowing for the simultaneous recovery of potassium and ammonium while leaving residual ammonium in the permeate (78). Addition of acid and pumping increase the operational cost of nano- or microfiltration (122), which could limit applications.

Membrane contactors function by allowing compounds to move between a gas and a liquid stream, again across a semipermeable membrane. As such, membrane contactors can be used to increase surface area and improve the efficiency of nitrogen recovery into an acidic liquid solution during ammonia stripping. According to the equations that govern mass transfer, the transfer of ammonia across hydrophobic membranes is most efficient at high concentrations. Altering conditions like pH and temperature can accelerate the mass transfer process (85), but at the cost of additional chemicals and energy. The benefits and limitations of this process are similar to those described above for ammonia stripping, except the membrane system costs and maintenance also need to be considered (84).

Currently, commercially available membrane processes are highly modularized, which makes upgrading existing infrastructure for nutrient recovery easier. Biological or chemical fouling issues are common for membrane-based processes, requiring regular cleaning and maintenance for consistent performance (120, 123). Because membranes can be used to either concentrate or purify nutrients, they are useful for recovering nutrients from diverse waste streams at a variety of feed concentrations. In addition, because of their modular nature, they can be flexibly installed for different flows and are suitable for distributed applications (123). Membranes are also semipermeable and as a result can retain cocontaminants, such as divalent metals; nevertheless, they do not have perfect selectivity and can thus have issues with cocontaminants in the nutrient-rich stream (124).

3.4. Electrochemical Processes

Although electrochemical technologies have been successfully demonstrated at a small field scale for carbon treatment and electricity generation (125), they have not been continuously operated at scale for the purpose of nutrient recovery from waste streams. Short-time-frame pilot-scale demonstrations of electrochemical phosphorus recovery from wastewater and nitrogen recovery from source-separated urine and digester supernatant have been successfully performed (86–88), providing guidance for future studies and scale-up. Several different electrochemical nutrient recovery technologies, including electrodialysis and microbial electrolysis, have been explored at this scale. A large number of laboratory-scale experiments have also been performed to investigate other electrochemical technologies and operating conditions, again with the goal of providing guidance for future studies and scale-up (126, 127). Electrochemical processes can also be used for pH modification, which can then be combined with precipitation, stripping, or membrane extraction for ammonia recovery. This application of electrochemistry has not been demonstrated continuously at large scale. Collection and recovery of precipitates from electrochemical processes remain challenging, in addition to issues of membrane fouling and high energy use.

Electrodialysis relies on membranes to concentrate charged species as they move from outer feed chambers toward electrodes of opposite charge. Once the ions move into a central chamber from the feed chamber, membranes restrict their further movement, resulting in the concentration of ions in the center chamber (94). Microbial electrolysis has also been used similarly, with bacteria oxidizing organic matter and using an anode as the electron acceptor, thereby providing the current to drive ionic migration and subsequent concentration. Electrodialysis has been successfully demonstrated with source-separated urine at a pilot scale, achieving nearly 90% nitrogen recovery as a concentrated solution (86). The energy requirements for this technology (46.8 MJ/kgN recovered) are high, and membrane fouling remains a challenge (86, 94). Electrodialysis has also been successfully used for nitrogen recovery from digester supernatant at a pilot scale (1,800 L/day) (88). While less efficient nitrogen recovery (23%) was observed than was demonstrated in other studies (e.g., 86), the energy expenditure (4.9 kJ/kgN recovered) was much less (88). Regular membrane cleaning was required.

Microbial electrolysis has also been demonstrated at a small pilot scale (33 L) with source-separated urine. Bacteria oxidize organic matter in a feed chamber, providing the current used to drive ammonia into a TransMembraneChemiSorption chamber, where it is concentrated as $(NH_4)_2SO_4$ (87). This demonstration was operated for approximately 6 months and achieved a nitrogen recovery of approximately 30%, with issues of unstable operation. The energy required to operate the system was 4.9 MJ/kgN. Finally, electrochemical phosphorus recovery has also been realized with human wastewater in batch at a pilot scale (22 L working volume), with up to 50% of the phosphorus in the waste recovered as hydroxyapatite (90).

Because electrochemical systems are modular in design, they show a great deal of promise for application with distributed treatment and can be deployed remotely and operated in batch mode. Nitrogen recovery appears to perform better with concentrated streams, such as urine. Capacity is an issue with electrochemical technologies, as they have been operated only at small field scales or less (128). In addition, the product from electrochemical systems tends to be a concentrate stream that may contain cocontaminants and is not likely to be as easily transported as chemical precipitates. In the case of electrodialysis, there is the need for membrane cleaning and limited experience with long operating periods. As a result, electrochemical technologies, while exciting, are not yet ready for deployment for nutrient recovery from waste.

EBPR: enhanced biological phosphorus removal

3.5. Biological Processes

Biological treatment processes concentrate nitrogen and phosphorus in biomass and then either use the biomass directly as fertilizer or extract/recover the nutrients for subsequent use. Two processes that have been applied at full scale are enhanced biological phosphorus removal (EBPR) and algal nutrient sequestration.

3.5.1. Enhanced biological phosphorus removal. EBPR has been used for decades for phosphorus removal from wastewater (129). As our understanding of the process has improved, its implementation at the full scale has expanded, with implementation for phosphorus removal and recovery from sidestreams, those concentrated streams recycled from solids handling back to the head of the treatment plant, also being more recently adopted (100, 129, 130). Although the process can be unstable and at times unpredictable (100, 130, 131), it is widely used. In general, EBPR operates by cycling biomass in a treatment system through anaerobic periods, followed by aerobic periods. During the anaerobic phase, specialized phosphate-accumulating organisms (PAOs) gain an advantage by taking up volatile fatty acids (VFAs) and incorporating them into carbon storage products within the cell (polyhydroxyalkanoates), with the release of some stored phosphorus and the use of stored glycogen. During the subsequent aerobic phase, the PAOs utilize stored polyhydroxyalkanoates to replenish glycogen stores and hyperaccumulate phosphorus as stored polyphosphate (130). The overall accumulation of phosphorus during EBPR can be high, resulting in 80–90% TP removal from the waste stream (100, 130, 131). Although EBPR is typically efficient for phosphorus removal, the recovery of phosphorus from EBPR sludge, as needed for downstream use, is not straightforward. Phosphorus recovery occurs via direct use of the high-phosphorus sludge, incineration of the sludge and use/extraction of high-phosphorus ash, chemical extraction of the high-phosphorus sludge, or anaerobic digestion with subsequent phosphorus recovery (132). In many of these processes, the potential for the presence of cocontaminants is high (132). As a result, care must be taken to manage the phosphorus-rich sludge or recover the phosphorus in such a way as to be protective of ecological and human health. Additional costs associated with the recovery of phosphorus from EBPR sludge include the cost of chemical additives for phosphorus extraction or precipitation or for the removal of toxic metal or metalloids.

To date, the application of EBPR has been for wastewater phosphorus removal. Its use for phosphorus removal and recovery from other waste streams should be possible, as long as adequate carbon, as VFAs, is present and the waste stream is not inhibitory to PAOs. Likewise, EBPR via a continuous process or a sequencing batch reactor is also possible, enabling somewhat distributed and scalable treatment. Because EBPR relies on biological phosphorus uptake, however, waste streams and process configurations need to be amenable to biological treatment (such as circumneutral pH and nontoxic feed).

3.5.2. Algal removal of nutrients. The growth of microalgae has also been demonstrated for efficient uptake of nitrogen and phosphorus from wastewater (95). Under diurnal cycles, algal processes can fix CO_2 through photosynthesis during the day and remove organics through heterotrophic growth at night. Both processes assimilate nitrogen and phosphorus into algal biomass that can be harvested as fertilizer (97). Algal growth is desirable with low-strength waste streams, while high concentration of nitrogen and organic compounds can be inhibitory to algal treatment

(98), with dilution or pretreatment of high-strength waste streams, such as anaerobic digestates, required (133). For efficient performance, algal processes require a large surface area for solar irradiation; therefore, they usually have larger footprints and lower energy demands than do other bacteria-based biological processes (134). These systems are preferably installed at centralized facilities without space limitation or at decentralized sites colocated with agricultural activities, facilitating treatment of both agricultural waste streams and the use of recovered nutrients as fertilizer. Similar to the challenges for EBPR, engineering challenges exist with respect to the efficient harvesting and processing of algal biomass to recover nutrients. In addition, eliminating cocontaminants, such as pathogens and heavy metals, is a challenge, depending on the waste stream used for algal nutrient recovery.

4. NUTRIENT RECOVERY FROM WASTE IN THE CONTEXT OF GLOBAL SUSTAINABILITY METRICS

4.1. Economic and Social Factors

Environmental sustainability can be classified as relative or absolute (135). Relative sustainability marks progress compared with past performance, while absolute sustainability ensures that environmental impacts stay within planetary boundaries (136). Given our current situation, circular economy principles need to be applied toward recycling valuable nutrients in waste (137). Nevertheless, while doing so, technologies to recover nutrients must not exacerbate other environmental issues, such as excessive energy use, unsustainable material extraction (e.g., mineral extraction and cement or steel use), or toxin release into the environment, with the goal of achieving absolute, not just relative, sustainability (137).

When advancing nutrient recovery from waste, social and environmental sustainability must be addressed. Paralleling the well-studied social challenges of water reuse, the adoption of nutrient recovery strategies will require an understanding of and sensitivity to the communities and individuals affected by these systems (14). Individual preferences for nutrient-rich reclaimed irrigation water are influenced by demographic characteristics (138). Public perceptions are also influenced by perceived health risks, religious prohibitions, political issues, and the degree of human contact with recycled water (139). When waste streams are used for nutrient recovery, a variety of cocontaminants can be present, affecting costs and environmental impact. Heavy metals increase treatment costs. Pathogens require additional disinfection, raising costs and environmental concerns. CECs challenge conventional treatments, leading to reliance on advanced, energy-intensive technologies for contaminant destruction and increasing costs and environmental impact while potentially exacerbating public concern, given the costs and new opportunities for technology failures that test trust in the scientific community and governing institutions.

The adoption of wastewater reuse programs has also been hindered by incoherent water quality requirements, which stem from two main issues: inconsistency over time, where standards and expectations for these technologies evolve due to changing regulatory landscapes and technological advancements, and diverse requirements that are not internally consistent, reflecting the differing needs of and specifications from various stakeholders or regions. This incoherence, characterized by both temporal variability and regional diversity in requirements, poses similar challenges for nutrient recovery from waste, complicating commercial development, public awareness, and stakeholder cooperation (140). To overcome these issues and enhance public acceptance, it is essential to build trust in regulators, consultants, academics, and elected officials and to ensure a fair and transparent decision-making process (141, 142).

The economic viability of nutrient recovery is also essential (143). Subsidies can align private interests with public benefits, fostering a favorable economic setting for these technologies (144).

Variations in demand for recovered nutrients, influenced by agricultural practices, commodity prices, and consumer preferences, can affect the potential revenue from selling these nutrients and thus the overall economics. Implementation costs for nutrient recovery approaches must, in the end, be attractive to a range of stakeholders and competitive enough to spur a nutrient management market. Regulatory bodies, by valuing these benefits, can frame policies to encourage technology adoption (143, 144). Changes in environmental and public health regulations can also impact the feasibility and economic aspects of nutrient recovery. For instance, stricter rules on nutrient discharge or higher waste disposal costs may incentivize nutrient recovery. All of the environmental, social, and economic factors described above, however, depend on the technological performance factors discussed in the rest of this section.

4.2. Energy Use

All of the technologies discussed in Section 3 require significant amounts of energy, either directly via electricity, fluid pressurization, or heat or indirectly through the embodied energy in the infrastructure. The environmental benefits and costs of these technologies can be contextualized via (*a*) the production of ammonia with the Haber–Bosch process, requiring approximately 32–71 MJ/kgN fixed (145), and (*b*) the mining of phosphate, requiring approximately 3–6 MJ/kgP. We can compare the energy footprint of technologies that recover nutrients from waste to these values. For example, in the case of nitrogen recovery using membrane contactors for digestate and urine, an energy demand in the range of the Haber–Bosch process (36 MJ/kgN) has been reported (80). Alternatively, nitrogen recovery from urine separation using precipitation and stripping has an energy demand almost five times higher (198 MJ/kgN removed) (64). Likewise, the energy demand for phosphorus recovery can range from 100 MJ/kgP using wet leaching and struvite precipitation to as high as 756 MJ/kgP with sludge melt gasification (101). While energy footprint analysis shows some benefit to the Haber–Bosch process, which accounts for 1.5–1.6 tonnes of CO_2 equivalent for each tonne of ammonia produced (146), one must consider that many of the technologies used for nutrient recovery from waste can operate on renewable electricity, which is a significant challenge for the Haber–Bosch process.

For nutrient recovery technologies, energy requirements can vary significantly on the basis of initial nutrient concentration, waste stream volume or flow, desired end concentration or product, equipment design and efficiency, and local conditions such as ambient temperature. Beyond direct energy impacts, each technology also has indirect environmental impacts associated with the production and transportation of the chemicals and equipment used. In the end, energy price fluctuations can significantly sway the economic viability of nutrient recovery operations, especially for energy-intensive processes such as membrane separation. If possible, synchronizing the variations in waste streams with the intermittency of renewable energy sources can further advance the carbon neutrality of nutrient recovery operations. By aligning waste processing with periods of high renewable energy availability, such as during peak solar or wind generation, operations can maximize their use of green energy and minimize carbon emissions. This harmonization not only enhances the environmental benefits of nutrient recovery but also offers cost savings by tapping into renewable energy when it is most abundant and inexpensive.

With respect to specific technologies, energy requirements vary. Membrane separation techniques such as reverse osmosis and nanofiltration are known to be energy intensive (147), escalating as nutrient concentrations increase (148). With ammonia stripping, waste streams are heated and alkalinized before air is introduced. Although energy consumption is significant as a result of heating requirements, it is generally less than that of membrane separation (149). Stripping can result in ammonia emissions if not properly managed, contributing to air pollution and the formation of fine particulate matter. Additionally, this process requires the use of alkali to increase pH, but the production of alkali can also have notable environmental impacts. Ion exchange can be passively operated; nevertheless, the process requires energy during the regeneration phase as well as treatment of the regenerant (54). The resins, typically synthetic, can also have significant environmental burdens in their production stage and pose a waste disposal issue at the end of their life. EBPR may be the least energy-intensive technology discussed above (130), with the energy required for aeration and maintaining appropriate process conditions typically lower than for other methods. The extraction of phosphorus from sludge requires further treatment, however, and EBPR can lead to emissions of greenhouse gases such as methane and nitrous oxide if not properly managed (130).

4.3. Scaling and Capacity

The volume of a waste stream and a technology's scalability and complexity play a pivotal role in determining the per-unit cost and environmental impact of nutrient recovery technologies. As a rule of thumb, economies of scale suggest that increases in the recovered volume often decrease per-unit costs up to a certain threshold. Nevertheless, while some technologies demonstrate economies of scale, others exhibit linear scalability or diseconomies of scale. Practical limitations, such as space constraints and feedstock availability, are critical when a technology's capacity to scale is evaluated. The complexity of a technology also impacts its operational capacity, requiring careful consideration of sophisticated, potentially costly systems and simpler, labor-intensive ones. Market capacity is another crucial aspect evoking consideration of the temporal and geographic demand for recovered nutrients and potential economic viability. Ultimately, assessing the capacity of nutrient recovery technologies requires an integrative approach, considering volume, scalability, practicality, operational capacity, and market demand to achieve sustainable and economically feasible solutions.

4.4. Consolidation and the Need for Infrastructure

The strategy of consolidation, which involves the collection of disparate waste streams at a unified processing site, can potentially enhance the operational efficiency of nutrient recovery. However, consolidation comes with several logistical challenges, such as a need for efficient infrastructure or transportation systems, including trucking (which is linked to emissions) and methods like pumping (which consumes electricity). It is essential to recognize that, while facilitating efficient treatment, centralized waste collection and management can lead to significant costs and environmental and social repercussions. Issues such as odor emissions, disruptions from broken pipes, and increased traffic are noteworthy. Additionally, the acceptability of recovered nutrients can vary; for example, struvite is dry, easy to transport, and relatively clean, whereas liquid-concentrated nutrients might be perceived as less desirable due to their more challenging distribution, use, and perceived cleanliness. The feasibility of consolidation is contingent upon the compatibility and collective contribution of the diverse waste streams to the nutrient recovery process (14). For example, in situations with low-volume wastes, such as source-separated urine, an intermediate collection point might be considered beneficial prior to centralized treatment. For other types of organic waste, this additional step introduces a layer of complexity as a result of the inherent variances in capacities, consistencies, and contamination levels across multiple waste streams.

Despite these potential obstacles, when they are effectively managed, consolidation can be a powerful tool in enhancing the efficiency and economic viability of nutrient recovery systems (150). In some instances, the amalgamation of multiple waste sources can even out inconsistencies in supply/flow and quality, offering a more stable and predictable feedstock for nutrient recovery.

Nevertheless, this process must be thoughtfully and carefully orchestrated to effectively balance the potential for increased chemical incompatibilities and contamination introduced by combining diverse waste sources. Residual wastes will also require proper disposal. Finally, if commercializing the recovered nutrients, effective distribution networks are essential, ideally employing renewable energy systems.

5. OUTLOOK AND NEXT STEPS

The recovery of nitrogen and phosphorus from waste streams is not only an environmental imperative but also a technological challenge that, if solved, holds significant promise for the future. As the world faces the dual challenges of resource scarcity and environmental degradation, our ability to recover nutrients from waste is critically important, offsetting the energy demands associated with traditional methods of fertilizer generation while decreasing nutrient-based pollution. However, nutrient recovery must not exacerbate other environmental issues, such as excessive energy use, unsustainable material extraction, and toxin release into the environment, with the goal of achieving absolute sustainability. Both emerging and more traditional technologies have shown potential in addressing the recovery of these vital nutrients, even from dilute waste streams such as municipal wastewater. Nevertheless, innovations are still needed to make this process both efficient and sustainable.

The commercial value of recovered nutrients, when used as fertilizers, can provide an economic incentive for further technological advancements in this domain. Yet, the road to widespread commercialization has challenges. Technological, economic, and social barriers have limited the large-scale adoption of nutrient recovery methods. For instance, the integration of infrastructure components, such as transportation systems and waste segregation facilities, is crucial for the success of centralized nutrient recovery strategies. When managing large and dilute waste streams, such facilities become even more challenging to site and operate. The push toward urine separation offers a promising avenue for energy-efficient and economically viable nutrient recovery, potentially revolutionizing the way we approach waste management. Source-separated urine offers the advantage of being a concentrated and consistent nutrient source. Although collection infrastructure will be needed, prior experience with similar decomposable waste streams, such as food waste, and pilot programs around the globe (**https://www.eawag.ch/en/department/eng/projects/water-hub**) provide a template upon which to build. Importantly, existing pilot- and full-scale options for both nitrogen and phosphorus recovery can be readily applied to source-separated urine. In the authors' view, further investment in developing viable urine separation, collection, and treatment systems as well as supporting policies to recover nitrogen and phosphorus is recommended.

Although the technological details of nutrient recovery are important, in the end the social and economic dimensions of nutrient recovery will determine where this potential step change in sustainability will go. Changes in environmental and public health regulations will most certainly impact the feasibility and economics of nutrient recovery, serving as a critical incentive to adopt behavior, infrastructure, and technical changes. For instance, stricter rules for nutrient discharge or higher waste disposal costs may incentivize nutrient recovery. The acceptance and adoption of the technologies presented above, or the further development of new technologies, will require a deep understanding of the communities they affect. Regulatory bodies have a pivotal role to play by framing policies that blend affordability with incentives, fostering an environment conducive to innovation and adoption. With the right mix of sustainable practices and technological advancements, we can pave the way for a future in which nitrogen and phosphorus recovery is not just feasible but also a cornerstone of our waste management strategies.

SUMMARY POINTS

1. Nutrient recovery from waste is a promising strategy that can address potential shortages or a lack of access to nutrients.
2. The feasibility of nutrient recovery from a particular waste stream depends on critical factors, including the concentration of nutrients in the waste, the quantity of the waste stream, the consistency of the waste stream, colocation with nutrient demand, collection infrastructure, and the occurrence of cocontaminants.
3. Municipal wastewater and some industrial wastewater streams are appropriate targets for nutrient recovery from waste, but cocontaminants must be managed to protect human and ecological health.
4. Ion exchange, precipitation, and stripping have been successfully applied at a pilot or full scale with feed streams of urine or digester supernatant.
5. Enhanced biological phosphorus removal (for phosphorus) and algal technologies (for nitrogen plus phosphorus concentration) have been demonstrated and applied at a pilot or full scale, but recovery of nutrients from the biomass can be a challenge.
6. Regulatory bodies can frame policies, including incentives and greater restrictions on nutrient discharge, to encourage nutrient recovery from waste.
7. Source-separated urine is an excellent target for nutrient recovery, but additional infrastructure is needed before recovery is viable

FUTURE ISSUES

1. Multiple viable and scalable technologies exist to recover nutrients from waste streams, but more research will improve the efficiency, scalability, operation, and predictability of these technologies.
2. Current nutrient recovery technologies require significant amounts of energy, either directly or indirectly through the embodied energy in the infrastructure.
3. The strategy of consolidation, which involves the collection of disparate waste streams at a unified processing site, can potentially enhance the operational efficiency of nutrient recovery. Changes in environmental and public health regulations will most certainly impact the feasibility and economics of nutrient recovery, serving as a critical incentive to adopt behavior, infrastructure, and technical changes.
4. Source-separated urine offers the advantages of being a concentrated and consistent nutrient source, although collection infrastructure will be needed; further investment in developing viable urine separation, collection, and treatment systems is recommended.

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AUTHOR CONTRIBUTIONS

All authors contributed equally to this article in terms of study conception and design, data collection and analysis, and article preparation and revision.

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