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Fertilizer demand and potential supply through nutrient recovery from organic waste digestate in California

Kevin D. Orner[a,b,*], Sarah J. Smith[c], Hanna M. Breunig[c], Corinne D. Scown[c,d,e,f], Kara L. Nelson[a,b,**]

[a] Department of Civil & Environmental Engineering, University of California, Berkeley, CA 94720, United States
[b] National Science Foundation Engineering Research Center for Re-inventing the Nation's Urban Water Infrastructure, Berkeley, CA 94720, United States
[c] Energy Analysis & Environmental Impacts Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States
[d] Lawrence Berkeley National Laboratory, Joint BioEnergy Institute, Berkeley, CA 94720, United States
[e] Biological Systems and Engineering Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States
[f] Energy & Biosciences Institute, University of California, Berkeley, CA 94720, United States

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ABSTRACT

Diversion of organic waste from landfills offers an opportunity to recover valuable nutrients such as nitrogen and phosphorus that are typically discarded. Although prior research has explored the potential for buildout of anaerobic digestion (AD) infrastructure to treat organic waste and generate energy, a better understanding is needed of the nutrient recovery potential from the solid and liquid byproducts (digestate) resulting from AD of these waste streams. We quantified the system-wide mass of nutrients that can potentially be recovered in California by integrating current and potential future AD facilities with existing nutrient recovery technologies. Based on a profitable build-out scenario for AD, the potential for nitrogen and phosphorus recovery by mass was greatest from municipal sewage sludge. The nutrient recovery (% total mass) was determined for three different end products for the combined organic waste streams: liquid fertilizer [38% of the total recovered nitrogen (TN)], struvite [50% TN, 66% total phosphorous (TP)], and compost (12% TN, 34% TP). Based on the profitable build-out scenario of AD facilities in California, the recovered nutrients would offset an estimated 11% of TN and 29% of TP of in-state synthetic fertilizer demand, whereas a scenario in which all technically recoverable biomass is collected and treated could offset 44% of TN and 97% of TP demand.

1. Introduction

Anaerobic digestion (AD) is widely used to treat a range of organic waste streams. In California, three recent Senate Bills are likely to spur additional investments in AD of organic waste by providing targets and guidance to: reduce methane emissions from manure and landfills (Senate Bill 1383 in 2016), increase renewable energy production (Senate Bill 100 in 2018), and control burning of agricultural and forestry waste (Senate Bill 1260 in 2018). For example, to meet the 2025 goal of 75% organic waste diversion from landfills in Senate Bill 1383, CalRecycle estimates that new infrastructure is needed to increase digester capacity from 1.1 million tons to 5.1 million tons per year of organic waste (CalRecycle, 2020). Meeting the 2025 goal with AD infrastructure would also increase biomethane production to approximately 400 million cubic meters (CalRecycle, 2020).

Separate from efforts to divert municipal organic waste, construction of dairy digesters has accelerated in California, driven by large greenhouse gas offset credits for renewable natural gas awarded through the Low Carbon Fuel Standards for diverting manure from lagoons (California Air Resources Board, 2018). Additionally, a previous study by members of our research team explored the total quantity of organic waste in California that could be treated in waste-to-energy systems, and the resulting energy potential (Breunig et al., 2017). The waste streams in this previous analysis were animal manure (AM), agri-food process residues (AF), agricultural crop residue (AC), and organic municipal solid waste (OMSW).

An anticipated challenge from the expansion of AD as a method for treating organic waste is that it generates a liquid digestate with a high

* Corresponding author at: Department of Civil & Environmental Engineering, West Virginia University, Morgantown, WV 26506, United States.
** Corresponding author at: Department of Civil & Environmental Engineering, University of California, Berkeley, CA 94720, United States.
E-mail addresses: kevin.orner@mail.wvu.edu (K.D. Orner), karanelson@berkeley.edu (K.L. Nelson).

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nutrient content (Lukehurst et al., 2010). The nutrients in this digestate, if directly discharged, would be added to the existing 9% of wastewater nitrogen that is already discharged to land and another 9% that is discharged to inland surface water in California (Tomich et al., 2015). Disposal of digestate derived from organic waste to the environment could further exacerbate eutrophication, which can lead to harmful algal blooms and have large economic repercussions to fisheries, tourism, property values, and recreation (Perry and Lubchenco, 2017; Water Environment Federation, 2014). The negative consequences of nutrient pollution may be intensified by rising temperatures and a growing world population (Larsen et al., 2016). Regulatory frameworks are already being considered in California to further reduce nutrient loads from point sources like wastewater to water bodies like San Francisco Bay (EBMUD, 2017).

The challenge of managing the liquid digestate may also represent an opportunity if the nutrients can be recovered to offset the use of synthetic fertilizers, which are manufactured through energy-intensive processes and non-renewable resources (Maurer et al., 2003). The Haber-Bosch process used to fix nitrogen from the atmosphere consumes large quantities of natural gas and accounts for 1–2% of total global energy demand (Philibert, 2018). Phosphorus, a finite resource, is almost exclusively mined from mineral deposits (Cordell et al., 2009). One option for nutrient recovery is direct land application of the liquid digestates. However, when compared to mineral fertilizer, disadvantages of direct land application include lower fertilizer value, higher potential for ammonia loss, higher transportation costs, odors, and additional undesirable constituents like metals and organic pollutants (Leverenz et al., 2019; Nkoa, 2014).

Alternatively, the nutrients in the digestate can be further concentrated to generate fertilizer products (Campos et al., 2019) and offset the economic and environmental costs of purchased synthetic fertilizer (Khoshnevisan et al., 2018). Combined with the nutrients present in the solid digestate (*i.e.*, biosolids), which can also be applied to land, there is potential to develop highly efficient systems for nutrient cycling (Campos et al., 2019; Tonini et al., 2013). While other studies have estimated global nutrient recovery potential from wastewater (Trimmer et al., 2017) and highlighted the ability of individual nutrient management technologies to recover nitrogen and phosphorus from organic waste streams (Campos et al., 2019; Ma et al., 2018; Tonini et al., 2013), to our knowledge no study to-date has complemented existing organic waste diversion efforts via a rigorous organic waste inventory combined with the large-scale (*e.g.*, state- or country-wide) potential for nutrient recovery from the resulting digestate.

The promise for this overall approach is recognized in the United Nations (UN) Sustainable Development Goals and the United States National Academy of Engineering (NAE) Grand Challenges, which both contain targets for sustainably recovering resources like nutrients and energy from waste streams (Perry and Lubchenco, 2017; Rosa, 2017). Thus, utilizing AD integrated with additional nutrient management technologies can address multiple UN Sustainable Development Goals and NAE Grand Challenges related to food, energy, water, poverty mitigation, waste reduction, and climate change.

The overall goal of the study presented here was to quantify the mass of nitrogen and phosphorus that can be recovered from organic waste streams by integrating nutrient recovery with AD. To make this question more tractable to answer, we focused specifically on nutrient recovery potential in California, using scenarios for 2020 and 2050. Specific objectives of the study were to: (1) quantify the nutrient content and total mass of the key organic waste streams; (2) determine the fate of nitrogen and phosphorus during AD, solid/liquid separation, and nutrient recovery from the solid and liquid streams; and 3) compare the quantity of recovered nutrients with the quantity of purchased synthetic fertilizer. The results provide insights that are relevant for other regions, and the methodology can be adapted to quantify nutrient recovery potential for other types or mixtures of organic wastes and to model different nutrient recovery technologies as more information is gained on their performance.

The state of California was chosen to explore the question of nutrient recovery and use because, in addition to producing the greatest quantity of organic waste of any state (Tomich et al., 2015) and making available a wealth of data, it has existing inefficiencies in nutrient cycling and has implemented strong policies to increase the recovery of energy and other value-added products from organic waste. In a recent nitrogen mass balance for the state of California, the mass of nitrogen imported as synthetic fertilizer (37%) was similar to that lost to the atmosphere (NO_x, N_2, and NH_3) (42%) through fossil fuel combustion, energy generation, and emissions from animal manure and fertilizer (Tomich et al., 2015). There is also significant leaching of nitrogen into groundwater (16%). Recovering nutrients from organic waste streams has the potential to improve nutrient cycling by reducing the use of synthetic fertilizer and decreasing losses to the atmosphere and groundwater (Bodirsky et al., 2014).

2. Materials and methods

The methodology to quantify the mass of nitrogen and phosphorus that can be recovered from organic waste streams treated with AD integrated with nutrient recovery is shown in Fig. 1. Multiple organic streams can be used as digester influent. The digester produces biogas and a nutrient-rich liquid effluent, which can be separated into liquids and solids for further treatment. The produced quantity of liquid and solid fertilizer was compared with the quantity of synthetic fertilizer purchased for in-state use.

The quantity of nutrients that can be recovered in California assuming biomass production rates forecasted for 2020 and 2050 was calculated for a baseline scenario (Scenario 1). Based on our literature review, we determined other common technology options and integrated them into additional scenarios: alternate separation processes (Scenarios 2A–E), alternate liquid nutrient recovery processes (Scenarios 3A–C), and an alternate solids treatment (Scenario 4). The processes, assumptions, equations, and calculations involved in each step are summarized in Table 1 and detailed in the sub-sections below.

2.1. Organic waste streams

Anaerobic digesters can be used to stabilize a wide range of organic

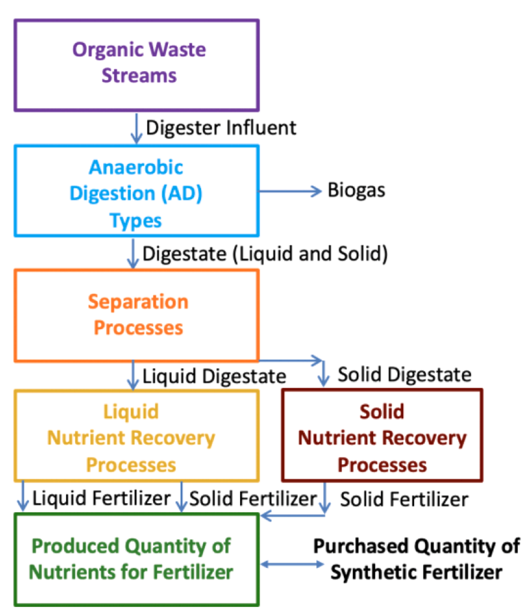

Fig. 1. Overview of steps to quantify the mass of nitrogen and phosphorus that can be recovered from organic waste streams.

Table 1
Overview of Category, Units, Equation, and Supplemental Information for Each Organic Waste Stream. A detailed summary of the input values and results for the high-market scenario is provided in Figure S1.

Category	Unit	Equation	Parameters	Table
Organic Waste Stream (Mass)	Mass of biomass / yr (M/yr)		Municipal Sewage Sludge (M_{mss})	Table S1
			Animal Manure (M_{am})	Table S2
			Agricultural Crops (M_{ac})	Table S3
			Agri-Food Process Residues (M_{af})	Table S4
			Organic Municipal Solid Waste (M_{omsw})	Table S5
Organic Waste Stream (Nutrients)	Mass of nutrients / Mass of biomass (N/M)	(M/yr) x (N/M) = Mass of nutrients / yr (N/yr)	Municipal Sewage Sludge (N_{mss})	Table S6
			Animal Manure (N_{am})	Table S7
			Agricultural Crops (N_{ac})	Table S8
			Agri-Food Process Residues (N_{af})	Table S9
			Organic Municipal Solid Waste (N_{omsw})	Table S10
Anaerobic Digestion Types	Percent Recovered (%AD)	(N/yr) x (%AD) = Mass of nutrients in digestate / yr (N_{AD}/yr)	Anaerobic Digestion (%AD)	Table S11
Separation Process	Percent to Liquid (%L), Percent to Solid (%S)	(N_{AD}/yr) x (%L) = Mass Liquid Nutrients / yr (N_L/yr), (N_{AD}/yr) x (%S) = Mass Solid Nutrients / yr (N_S/yr)	Belt Press ($\%L_{bp}$)	Table S12
			Sieve Drum ($\%L_{sd}$)	Table S13
			Screw Press ($\%L_{sp}$)	Table S14
			Sieve Centrifuge ($\%L_{sc}$)	Table S15
			Decanter Centrifuge ($\%L_{dc}$)	Table S16
			Brushed Screen ($\%L_{bs}$)	Table S17
Liquid Nutrient Recovery Process	Percent of Liquid Nutrients Recovered (%LR)	(N_L/yr) x (%LR) = Mass Liquid Recovered Nutrients / yr (N_{LR}/yr)	Struvite Precipitation ($\%LT_{sp}$)	Table S18
			Ammonia Stripping ($\%LT_{as}$)	Table S19
			Thermal Distillation ($\%LT_d$)	Table S20
Solid Nutrient Recovery Process	Percent of Solids Nutrients Recovered (%SR)	(N_S/yr) x (%SR) = Mass Solid Recovered Nutrients / yr (N_{SR}/yr)	Composting ($\%ST_c$)	Table S21

waste streams such as AM, AC, AF, OMSW, and municipal sewage sludge (MSS) (Lukehurst et al., 2010). These five organic waste streams were chosen as they represent the largest organic waste streams by mass available for nutrient recovery. Three projections were used to represent the potential availability of organic waste streams in 2020 and 2050: gross, technical, and market. Gross refers to the total mass of the organic waste stream (including waste currently collected and not currently collected), and the technical portion is the fraction of the gross mass that would be feasible to collect, can be used as an input into AD, and is not used in another market. Market refers to the in-state biomass that could be profitably diverted from the organic waste stream based on current cost estimates and a range of electricity selling prices (combined market and policy-related revenues) per the Lawrence Berkeley National Laboratory (LBNL) Organics Recycling Facility Investment model (Scown et al., 2019; Smith et al., 2021)). Low- and high-market scenarios are modeled based on biomethane prices ($/Mcf) of 15 and 25, respectively, in 2020 and 12 and 60, respectively, in 2050. The low-price values are intended to represent expected energy market prices, while the high-price values are intended to reflect prices that could be achieved through a mix of consumer renewable energy mark-ups and monetary environmental subsidies. It should be noted that these market scenarios are conservative, as they only consider potential profit-driven private sector investment in AD facilities rather than the aggressive infrastructure investments that will likely be required to meet state landfill diversion goals.

The mass of organic wastes (M) produced in each year (in wet and bone dry Mg) were previously calculated for AM, AC, AF, and OMSW for the years 2020 and 2050 (Breunig et al., 2017). The largest contributor to the AM category was dairy manure. The AC category included culls from 39 food crops and residue from 51 food crops, including almonds, hay, grapes, and rice. The AF category included residues from 17 categories such as almond shells, almond hulls, brewery waste, walnut shells, and rice hulls. Lastly, the OMSW category contained categories such as green waste and food waste.

MSS is currently treated in California at several hundred wastewater treatment plants through processes such as AD, aerobic digestion, sludge lagoons, chemical oxidation, and lime stabilization (Crites and Tchobanoglous, 1998). The MSS that is currently anaerobically digested at 130 California facilities was considered to represent both the technical and market biomass as the facilities are already built and operated (Breunig et al., 2017). The gross biomass (kg/day) of MSS includes the remaining WWTPs that do not anaerobically digest their sludge, and therefore was calculated based on existing total flow at each of California's 497 wastewater treatment plants in 2012 (Table S1) (EPA, 2012).

The mass of nutrients (N) per wet mass of biomass was estimated from published values identified through a comprehensive review of literature for Total Nitrogen (TN), Ammonium-Nitrogen (NH_4^+-N), and Total Phosphorus (TP) in each organic waste stream. Table 1 contains an overview of the categories, units, outputs, parameters, and supplementary tables (Tables S1-S21); detailed calculations and literature values are found in the supplementary tables. It was assumed that TP was predominantly PO_4^{3-}-P due to sparse literature on phosphate concentrations in organic waste streams. Nutrient mass concentration (Table S22) varies widely for different sub-categories of some waste streams (*e.g.* meat waste vs. fruit waste for AF). However, AD facilities typically take in a wide range of these wastes and do not have information about the specific breakdown; therefore, average values were calculated for each waste stream as a whole.

2.2. *Anaerobic digestion types*

AD is used to stabilize solids and produce biogas that can be used as an energy resource (Breunig et al., 2017). During the digestion process, organic nitrogen and phosphorus are typically converted into inorganic ammonium and phosphate, respectively (Orner et al., 2020). Two types of AD used to process organic waste streams are dry AD and wet AD. Dry AD facilities, as well as stand-alone wet AD facilities (*i.e.*, not part of a municipal wastewater treatment plant), are a growing sector, particularly in California where facilities are being built to handle more diverse waste streams to aid in landfill diversion (CalRecycle, 2020; Goldstein, 2018; Satchwell et al., 2018). Dry AD or wet AD may be more viable for some organic waste streams over others (see Tables 2–S5) because digestates have different biological, chemical, and physical properties. MSS, AM slurries, and high-moisture AF are often treated with wet AD. Wet AD can also co-digest sewage sludge with waste organics from food processing facilities at WWTPs to provide benefits such as increased methane production (Lee et al., 2019). Food-only OMSW (*e.g.* cafeteria or grocery store waste) can often go to wet AD while mixed or co-mingled OMSW (including green waste, paper products, etc.) would typically go to dry AD. Higher-solids AM and AC are commonly treated with dry AD, though liquid can be added during wet AD to treat some higher-solids wastes.

Published literature was reviewed to determine the percent recovery (%AD) of TN, NH_4^+-N, and TP during AD. Although nutrient recovery percentages during AD are likely dependent on context-specific factors such as initial nutrient content, solid content, operation temperature, and hydrolysis extent, currently this level of context-specific data is unavailable for all combinations of the context-specific factors. Therefore, more general percent nutrient recovery data was used. Without substantial evidence to suggest differences, we assume that nutrient recovery percentages in wet AD holds true for dry AD. Even though TN and TP content is generally maintained during AD, digestate from wet AD has a much higher water content than dry AD. Therefore, the concentration of nutrients may be higher in dry AD than wet AD, which will impact subsequent separation and nutrient recovery (Xu et al., 2018). A review of literature indicated that after AD approximately 89% of TN and 95% of TP end up in the digestate effluent, and the percentage of NH_4^+ (341%) and PO_4^{3-} (140%) (Table S23) increases from the digester influent to the digester effluent due to the digestion of organic nitrogen and phosphorus (Orner et al., 2020).

2.3. Separation processes

The nutrient-rich digestate that leaves the anaerobic digester can be separated into its liquid and solid components for further treatment and easier transport (Lukehurst et al., 2010; Sanscartier et al., 2012). Separation has the benefits of producing a liquid stream from which nutrients are efficiently recovered. Other benefits of separation may include improved matching of liquid and solid products to crop needs, reduced storage and transportation volume, and reduced stirring (Moller and Muller, 2012). Types of physical separation processes include belt press, sieve drum, screw press, sieve centrifuge, decanter centrifuge, and brushed screen. The separator equipment can be classified as low-performance (*e.g.* screw press), which are typically used for feedstocks with high solids content, or high-performance (*e.g.* centrifuge, rotary drum), which are generally used for low-solids feedstocks (Guilayn et al., 2019); high-solids digestates may have clogging issues in high-performance separation processes (Hjorth et al., 2010). The effluent of dry AD will likely require less separation of liquids and solids than wet AD due to its lower water content, thereby reducing costs from energy use (Riya et al., 2020). It is also possible to couple low-performance separation (*e.g.* screw press) of the digestate followed by high-performance separation (*e.g.* sieve or centrifuge) of the subsequent liquid fraction (Guilayn et al., 2019). In California, the most common type of separation process utilized is the screw press, therefore the screw press was chosen as the separation process for each digestate in the baseline scenario (Guilayn et al., 2019). Decanter centrifuges are the most effective at separating phosphorus into the solid form; however, it has the highest costs for both construction and operation and is therefore typically only used for very large systems (Lukehurst et al., 2010). Nonmechanical methods such as polymer additives can improve separation (Hjorth et al., 2010).

A literature review was utilized to determine the percentage of nutrients allocated to liquids (%L) and solids (%S); the sum must add to 100%. The effectiveness of separation processes varies widely. When digestate is separated, the percentage of TN in the liquid can range from 68% (belt press) to 86% (sieve drum, brushed screen). Likewise, the percentage of TP in the liquid can range from 29% (decanter centrifuge) to 84% (brushed screen) (Table S24). The nutrient recovery percentage during alternative separation processes were calculated in Scenarios 2A–E.

2.4. Nutrient recovery processes for liquids

Once separation has occurred, the liquid digestate, rich in NH_4^+ and PO_4^{3-}, is available for further treatment and nutrient recovery (Brändli et al., 2007). Example liquid nutrient recovery technologies include struvite precipitation, ammonia stripping, and thermal distillation (Vaneeckhaute et al., 2017). The precipitation of struvite ($MgNH_4PO_4 \bullet 6H_2O$) has been commercialized at full-scale for fertilizer production at industrial and municipal wastewater treatment plants (Ostara, 2021) and struvite can also be recovered from AM digestate (Orner et al., 2020). The precipitation process often requires the addition of magnesium and a base to recover NH_4^+ and PO_4^{3-} in the form of struvite fertilizer (Le Corre et al., 2009). Ammonia stripping, which involves transferring $NH_{3(aq)}$ into a gaseous phase at high pH followed by absorption back into an acidic liquid phase to stabilize it as NH_4^+, requires the addition of a base and an acid (*e.g.* sulfuric acid or nitric acid) and can be used to produce a liquid fertilizer (*e.g.* ammonium sulfate or ammonium nitrate) (Vaneeckhaute et al., 2017). This technology has also been commercialized at full-scale (*e.g.* Anaergia) to recover up to 90% of NH_4^+ (Anaergia, 2020). Thermal distillation utilizes heat to promote evaporation of $NH_{3(aq)}$ followed by condensation, and can be combined with an acid to produce a liquid fertilizer such as ammonium sulfate or ammonium phosphate (Tun et al., 2016). Thermal distillation has achieved 95% NH_4^+ recovery from digestate at the pilot scale (7500 gal/d) and is currently being implemented at full-scale (Leverenz et al., 2021, 2019). Technologies such as ion exchange (Tarpeh et al., 2018) and the Vuna process, which uses partial nitrification, activated carbon filtration, and distillation to capture nutrients and eliminate pathogens (Vuna, 2020), are viable for recovering nutrients from urine, but have not yet been widely tested on digestate and are therefore not considered further here.

Liquid nutrient recovery processes such as struvite precipitation (Simoes et al., 2018), ammonia stripping (Anaergia, 2020), and thermal distillation (Leverenz et al., 2021) recover phosphorus and nitrogen at different efficiencies (Table S25). A review of literature was used to determine the percent nutrient recovery of each liquid nutrient recovery process. Struvite precipitation is the most effective at recovering TP (75%) while also recovering some TN (10%). To remove additional TN, ammonia stripping and thermal distillation can be used as a second treatment step. Liquid nutrients were allocated to a liquid nutrient recovery process for the baseline scenario based on which technology had the highest recovery percentage as reported in literature: nitrogen (thermal distillation) and phosphorus (struvite) (Leverenz et al., 2021; Simoes et al., 2018). Nutrient recovery for alternative processes were calculated in Scenarios 3A–C.

2.5. Nutrient recovery processes for solids

Multiple processes exist for further treating the biosolids. Class B biosolids that have detectable levels of pathogens can be land applied with restrictions, whereas Class A biosolids that have undetectable levels of pathogens can be land applied without restriction (US EPA, 1992). Land applied biosolids would theoretically recover all nutrients. Composting the biosolids has the potential to further inactivate pathogens through sufficient time and temperature (Grewal et al., 2006) and produce a soil amendment, often through the addition of a bulking agent (Bustamante et al., 2013). Landfilling biosolids requires transport and landfill space while offering no recovery.

A literature review was utilized to determine the percent nutrient recovery of each solid treatment process (%SR) (Table S21) (Tiquia and Tam, 2000). In the baseline scenario, all solid digestate is assumed to be composted to meet Class A designation, which would allow unrestricted land application in agriculture. In Scenario 4, the nutrient recovery percentage is calculated assuming the digested solids do not receive further treatment.

2.6. Produced quantity and desired quantity of nutrients for fertilizer

Adding the mass of recovered nutrients from liquid treatment to the mass of recovered nutrients from solid treatment results in the produced quantity of recovered nutrients (N_P) that can be used as fertilizer. The produced quantity was compared to the desired quantity of nutrients (N_D), represented in this study as the mass of purchased synthetic fertilizer. We assume that the produced quantity could be used as a 1:1 offset of synthetic fertilizer. While this is likely reasonable for the concentrated fertilizers produced from the separated liquid digestate, nutrients in compost may not be fully utilized in all locations as farmers may require more concentrated products or more consistent nutrient uptake depending on their crop. The mass of synthetic fertilizer was calculated by multiplying the average mass of nutrients in purchased synthetic fertilizer (Breunig et al., 2019; California Department of Food and Agriculture, 2016; Tomich et al., 2015) by a growth factor (1.8% assumed between 2015 and 2020 and 15.5% between 2020 and 2050) based on the projected percent increase in gross agricultural crops in California (Breunig et al., 2017).

2.7. Sensitivity analysis

A sensitivity analysis was conducted for each process technology by adding or subtracting one standard deviation from the mean nutrient recovery. The sensitivity factor (SF) was calculated by dividing the percent change in output by the percent change in input. A higher SF indicates a more sensitive process technology. Because there was insufficient information regarding the variability of nitrogen recovery by thermal distillation, a standard deviation of 20% was assumed in accordance with prior practice (Kavvada et al., 2017).

3. Results and discussion

In the subsequent sections, we explore in detail the model results starting with characterization of the different organic waste streams, then following the nutrients through each step of treatment needed for fertilizer production.

3.1. Organic waste streams

The produced daily biomass that was feasible to treat by AD in the 2020 high-market model scenario for organic waste streams (encompassed by MSS,AM,AC,AF, and OMSW) was 9.4 Gg (9400 Mg), which was only 11% of the daily gross biomass of 87 Gg (Fig. 2). OMSW (44%) was the largest contributor due to the high intake tonnages possible when the renewable electricity is valued above-market. In the low-market scenario, as defined by the lower value of the electricity produced by AD, MSS was the largest contributor of daily biomass at 55% (2.5 out of 4.5 Gg), followed by AF (25%) and OMSW (19%). The large contribution from MSS can be mainly attributed to the abundance of existing infrastructure to treat MSS at municipal wastewater treatment facilities. In 2050, the modeled daily gross biomass of organic waste was 99 Gg. The largest contributors in the high-market scenario in 2050 were OMSW (37%) and AF (24%), although AC (13%) and AM (9%) became larger contributors in this scenario. The percent contributions of each organic waste stream varied widely in the gross, technical, and market scenarios due to the differences in feasibility and cost of collection, transportation, and treatment.

It was estimated to be technically feasible to collect, and therefore send to AD processes, about a third of the organic wastes, due primarily to limitations in the feasibility of collecting agricultural on-field residues, lack of digesters at smaller wastewater treatment facilities, and the difficulties of collecting post-consumer waste streams that are reasonably uncontaminated (Breunig et al., 2017). Additionally, not all organic waste is viable for anaerobic digestion (*e.g.*, cardboard and lumber) (Table S5). The technical scenario only included organic wastes not included in another market; organic wastes that were already re-applied to land were excluded. However, to fully utilize the energy and nutrient recovery potential in these wastes, AD facilities must be built in significant quantities, which requires either a viable (profitable) business opportunity or significant public sector organization and investment. These opportunities appear to be limited currently, which results in the low-market scenario tonnages shown in this work, though as organics waste diversion policies increase in scope and enforcement, as is ongoing in California, the amount of waste sent to AD facilities will likely trend closer to the technically-recoverable quantities. For example, the mass of OMSW in the 2020 market-high scenario is projected to increase from 4.1 to 6.3 Gg/d by 2050 even though the technical quantity only increases from 7.5 to 7.7 Gg/d in the same period due

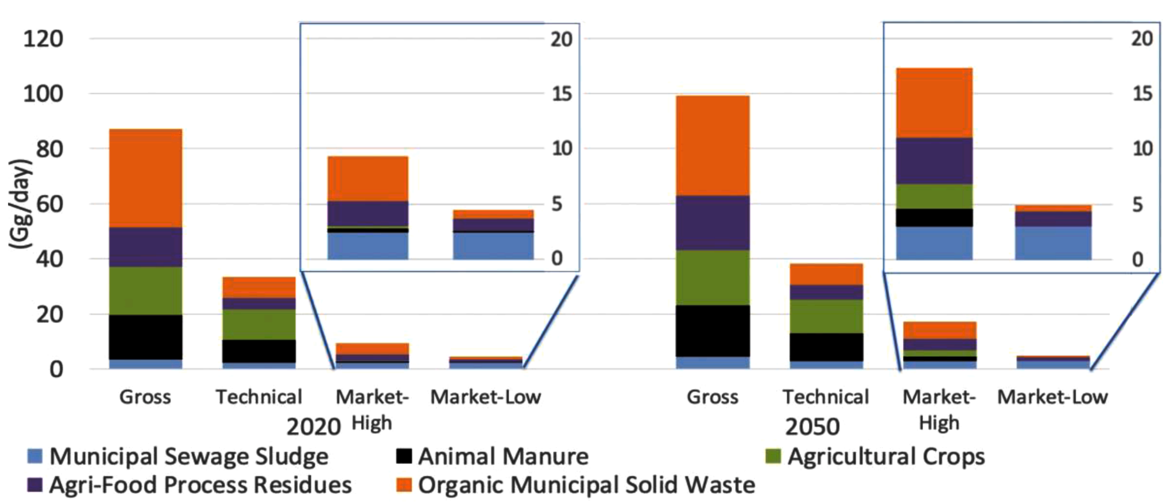

Fig. 2. Dry mass per year (Gg/day) of gross, technical, and market (low, high) organic waste streams in California in 2020 and 2050. The insets are zoomed-in views of the market scenarios, and the 2050 inset scale also applies to the 2020 inset.

to more viable business opportunities driven by policies such as SB 1383. If the mass of all recovered organic waste transitioned from the high-market quantity to the technical quantity, the mass would quadruple (9 to 33 Gg/d) in 2020 and more than double (17 to 38 Gg/d) in 2050.

The majority of organic waste (and its embedded nutrients) in the gross scenario in Fig. 2 that is currently not technically recoverable is often discharged to surface water or disposed of at landfills (further discussed in Section S1). Discharging organic waste streams to the environment can contribute to eutrophication, while disposing at landfills can increase greenhouse gas emissions (Cal Recycle 2020). Alternatively, direct land application of organic waste, while providing benefits of returning beneficial nutrients to crops, has limitations such as uncertain nutrient quantities and nutrient transfer, application restrictions for food ground crops, and potential exceedances of water quality regulations (Conijn et al., 2018).

Given the market biomass for each organic waste stream and their corresponding nutrient mass concentrations and total solids percentages (Table S22), the nutrient loadings (Mg/day) to anaerobic digesters in the 2020 high-market scenario were 204 for TN (Fig. 3A), 117 for NH_4^+-N, and 76 for TP (Fig. 3B). Together, OMSW and MSS made up 80% of feedstock for TN and 88% for TP. MSS was the largest contributor for TN (55%) and TP (75%). In 2050 the total nutrient loadings (Mg/day) almost doubled to 361 for TN (Fig. 3C), 195 for NH_4^+-N, and 122 for TP (Fig. 3D). Whereas AC contributed a negligible percentage of TN and TP in 2020, in 2050 the contributions were estimated to be 12% of TN and 6% of TP.

Although a larger mass of organic waste was available from OMSW than the from the other waste streams in the high-market scenario (Fig. 2), more nutrients were available from MSS (Fig. 3) because MSS

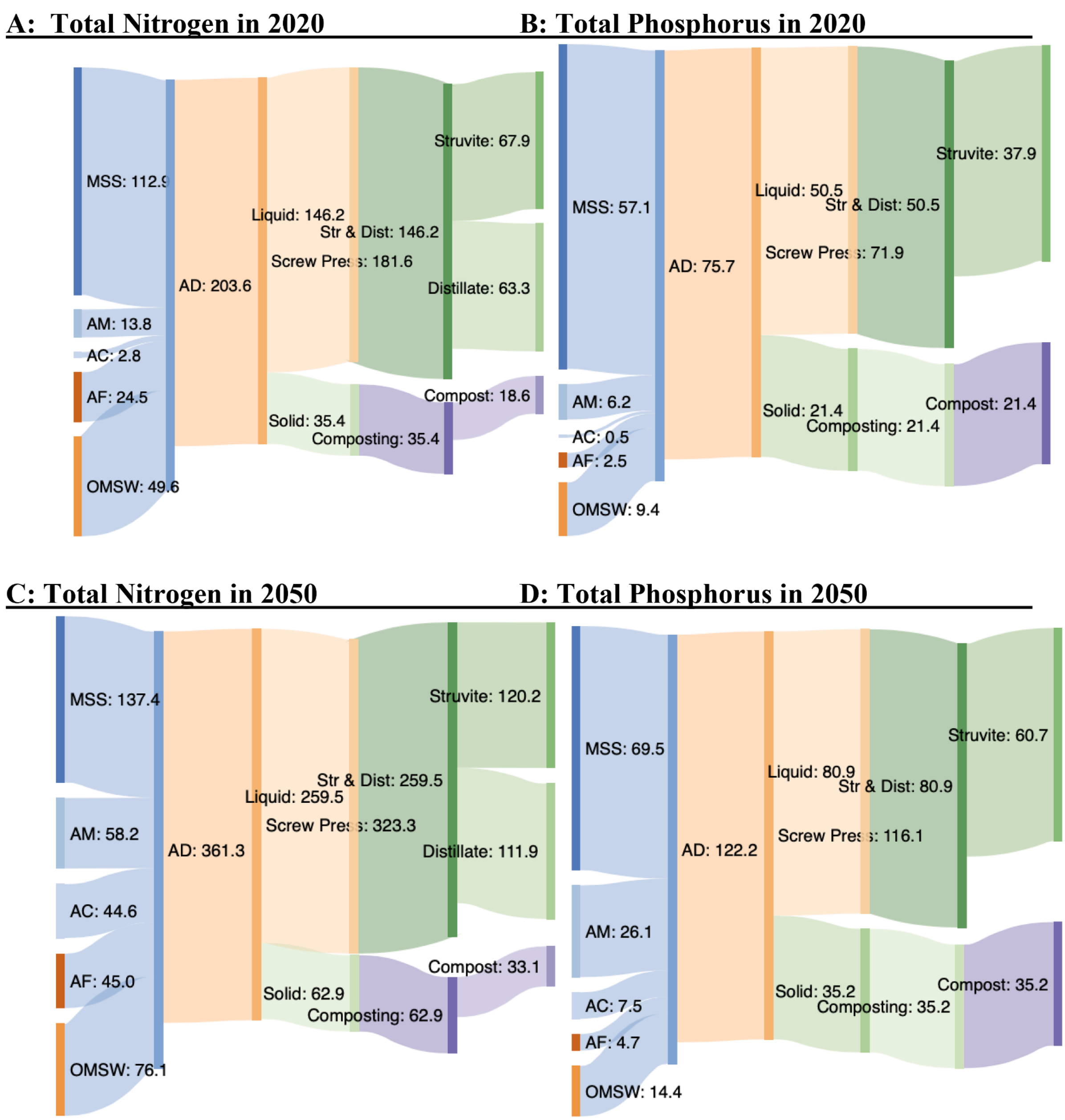

Fig. 3. Mass (Mg/d) of Total Nitrogen in 2020 (A), Total Phosphorus in 2020 (B), Total Nitrogen in 2050 (C), and Total Phosphorus in 2050 (D) from five organic waste streams through anaerobic digestion, separation, and nutrient recovery in the baseline high-market scenario. Abbreviations include MSS (Municipal Sewage Sludge), AM (Animal Manure), AC (Agricultural Crops), AF (Agri-Food Process Residues), OMSW (Organic Municipal Solid Waste), and AD (Anaerobic Digestion). Data in the figure is based on the equations in Table 1 and analysis in Tables S1-S21.

was the highest-strength waste (g of TN, NH_4^+-N, and TP per kg organic dry weight). MSS contained 46 g TN/kg, followed by AM, AC, OMSW, and AF (37.9,19.7,12.0, and 10.8 g TN/kg, respectively. The significant nutrient fluxes from streams other than MSS (Fig. 3) signal an opportunity to provide infrastructure to recover nutrients from these alternate streams.

3.2. Nutrient recovery

For the remainder of the analysis, only the high-market scenario is presented to calculate nutrient recovery potential because we believe it is the most representative future scenario, in between the low-market scenario and what is technically feasible. A detailed summary of the input values and results for the entire high-market analysis is provided in Fig. S1; the comparable calculations and results for the technical scenario are presented in Fig. S2. In Fig. 3, the mass of nutrients recovered from each organic waste stream through each treatment step [anaerobic digestion (Table S23), solid/liquid separation (Table S24), and nutrient recovery (Table S25)] is presented. Under the high-market scenario in 2020, treating all the organic waste streams with AD would produce a digestate that contains 182 Mg/day of TN and 72 Mg/day of TP (Fig. 3A and B). If these nutrient-rich digestates become runoff, much of the nutrients would likely reach surface waters, contributing to widespread eutrophication. To evaluate the potential for nutrient recovery from digestate, the baseline treatment process was solid-liquid separation by screw press, followed by composting of the solids, and struvite precipitation and thermal distillation for the liquid stream. The result was 131 Mg/day of TN (struvite plus distillate) and 38 g/day of TP (struvite) that can be recovered from the liquid digestate (Fig. 3A and 3B). The composting step for solids treatment reduced the nitrogen recovery (53% of TN) compared to no treatment of solids (Table S25), which resulted in 19 Mg/day of TN and 21 Mg/day of TP in the recovered compost.

The combined produced quantity of nutrients for fertilizer was 150 Mg/day of TN and 59 Mg/day of TP in 2020 (Fig. S3). The majority of the TN came from MSS (60%) and OMSW (26%). The majority of the TP came from MSS (75%). Approximately 88% of the combined quantity of TN was derived from the liquid digestate in the form of solid struvite fertilizer and liquid distillate (Fig. 3A). The ammonium in the liquid distillate can be recovered with acids to produce liquid fertilizers such as ammonium sulfate and ammonium phosphate. Similarly, approximately 64% of the combined quantity of TP is derived from the liquid digestate (Fig. 3B). As a result, the compost recovered from separated solids has only 12% of the TN and 36% of the TP that was present in the original waste stream.

It is interesting to note that the five organic waste streams have varied N:P molar ratios after the anaerobic digestion step (Table S22). While the N:P molar ratios in MSS (4.7) and AM (5.5) are lower, the N:P molar ratio in AC (14.8), OMSW (13.0), and AF (24.4) are much higher. The N:P molar ratio may be expected to vary between dry AD digestate and wet AD digestate as dry AD can accept a wider variety of organic wastes than wet AD. An N:P molar ratio of near one is beneficial for struvite precipitation, due to the stoichiometric ratio of 1:1 N:P in the mineral. When the N:P molar ratio is higher, an alternative or additional technology is needed to increase the recovery of nitrogen, as demonstrated in this analysis by ammonia stripping or thermal distillation.

To put the quantities of nutrients that can potentially be recovered from AD in perspective, we provide a comparison to purchases of synthetic fertilizer. The amount of synthetic fertilizer bought in California in 2015 was 1320 Mg per day of TN and 200 Mg per day of TP. The amount of TN and TP in purchased synthetic fertilizer is expected to rise to 1340 Mg per day and 205 Mg per day by 2020, respectively. Our overall model results indicate that the potential for production of fertilizer from organic wastes in California would offset 11% of TN and 29% of TP of synthetic fertilizer purchases in the high-market scenario for AD in 2020. In a similar model for the year 2050, organic production of fertilizer would offset 17% of the desired 1550 Mg of TN and 40% of the desired 237 Mg of TP. The offset would be greater if all technically-feasible organic waste was treated by AD with nutrient recovery - 44% of TN and 97% of TP in synthetic fertilizers (Fig. S2). In the technical scenario in 2020, animal manure is the leading contributor of nitrogen (41%) and phosphorus (54%) (Fig. S4). Therefore, an important opportunity exists to offset or even replace purchased synthetic fertilizer by implementing nitrogen and phosphorus recovery technologies to treat digestate derived from organic waste streams. However, the absence of strong market drivers such as greenhouse gas offset credits currently limits the potential for AD, which inherently limits the potential for nutrient recovery via treatment of the digestate.

In addition to the baseline scenario, we evaluated alternate technology options for solid-liquid separation, treatment of the liquid digestate, and treatment of the solids. The results are summarized in Table 2, and compared to the baseline scenario already presented, in which 79% of TN and 79% of TP can be recovered from the input organic waste streams (Scenario 1). Separation process did not impact overall TN recovery, but shifted the percent recovered between the products recovered from the liquid and the solid; TP recovery varied depending on the process chosen (Scenarios 2A–E). As compared to the affordable and ubiquitous screw press, use of a decanter centrifuge contributed to recovery of an additional 9% of TP due to its high-speed centrifugation causing more phosphorus to end up in the solid form where it is more effectively recovered (Scenario 2D). Therefore, this technology may be of interest to wet AD facilities in the future if phosphorus fertilizers become a valuable byproduct. However, while more phosphorus was technically recovered in the solid form through compost, the phosphorus recovered through the liquid digestate is in a more consistent form that could provide greater value both economically and environmentally, as it is more likely to be suitable for use as a drop-in fertilizer replacement. Eliminating a secondary liquid treatment step that includes nitrogen recovery (thermal distillation) dropped the TN recovery percentage from 79 to 16% (Scenario 3A). Likewise, eliminating struvite precipitation reduced the TP recovery percentage from 79 to 30% (Scenario 3B). Facilities nonetheless may choose to invest in only one of these processes, depending on the relative cost and resource (energy and material) intensity of each and the fertilizer markets available to them. Lastly, eliminating composting as a final treatment step for solids improved the TN recovery percentage from 79% to 88%, but the recovered product may have restrictions for land application due to higher pathogen risk (Scenario 4).

3.3. Sensitivity analysis

The output of a sensitivity analysis of process technologies on recovery of TN and TP is shown in Table S26. Note that the overall TN and TP recovery was the combined recovery from products derived from both the separated liquids and solids. The TN recovery percentage was most sensitive to variability in nutrient recovery in the anaerobic digester (SF = 0.80); a drop from 89% TN recovery to 69% recovery during AD resulted in a decrease in overall TN recovery from 81 to 65%. Separation (SF = 0.36), nutrient recovery via thermal distillation (SF = 0.35), and composting (SF = 0.20) had moderate sensitivity. The sensitivity of liquid nitrogen recovery via struvite precipitation (SF = 0.02) was low because nitrogen that was not recovered in struvite was recovered by thermal distillation. In contrast, liquid nutrient recovery via struvite precipitation (SF = 0.65), AD (SF = 0.56), composting (SF = 0.32), and separation via screw press (SF = 0.21) all moderately affected TP recovery. Given the low confidence in the variability of nitrogen recovery by thermal distillation, and the sensitivity of the overall recovery to this process, more effort should be devoted to developing and characterizing this process.

Table 2
Percent Nitrogen and phosphorus recovery from multiple treatment scenarios.

#	Scenario	Separation Process	Liquid Treatment Process	Solid Treatment Process	% Orig. TN Recovered	% Orig. TP Recovered
1	Baseline	Screw Press	Struvite Precip. and Distillation	Composting	79%	79%
2A	Alternate Separation: Belt Press	*Belt Press*	Struvite Precip. and Distillation	Composting	74%	78%
2B	Alternate Separation: Sieve Drum	*Sieve Drum*	Struvite Precip. and Distillation	Composting	81%	76%
2C	Alternate Separation: Sieve Centrifuge	*Sieve Centrifuge*	Struvite Precip. and Distillation	Composting	81%	78%
2D	Alternate Separation: Decanter Centrifuge	*Decanter Centrifuge*	Struvite Precip. and Distillation	Composting	76%	88%
2E	Alternate Separation: Brushed Screen	*Brushed Screen*	Struvite Precip. and Distillation	Composting	82%	75%
3A	Alternate Liquid Treatment: Struvite Precip. Only	Screw Press	*Struvite Precip.*	Composting	16%	79%
3B	Alternate Liquid Treatment: Thermal Distillation Only	Screw Press	*Distillation*	Composting	79%	30%
3C	Alternate Liquid Treatment: Ammonia Stripping	Screw Press	*Ammonia Stripping*	Composting	70%	30%
4	Alternate Solids Treatment:	Screw Press	Struvite Precip. and Distillation	*None*	88%	79%

3.4. Implications of nutrient management and future research

Anaerobic digesters are increasingly being used to treat multiple organic waste streams, and nutrient recovery can complement existing energy recovery at these facilities to offset synthetic fertilizer production and reduce eutrophication potential. Wastewater treatment plants like East Bay Municipal Utility District (EBMUD) in Oakland, CA are already augmenting their existing anaerobic digesters with food waste to increase biogas production. Other treatment plants such as Madison Metropolitan Sewerage District's Nine Springs plant in Madison, WI produce struvite from the liquid stream of their anaerobic digesters. Integrating nutrient recovery from both the solid and liquid digestate streams at treatment plants in California could considerably offset synthetic fertilizer purchases given that synthetic fertilizer represents 37% of all nitrogen imports in CA and 11% of TN was offset in the 2020 high-market scenario (Tomich et al., 2015). Likewise, capturing nitrogen as fertilizer could reduce nitrogen losses to the environment. For example, N_2 gas represents 13% of California nitrogen exports (Tomich et al., 2015), and N_2 emissions during mainstream nitrification/ denitrification could be reduced through sidestream nutrient recovery from MSS via AD. The key inputs and losses from the nitrogen cycle in California are similar to those in Europe and Asia, although California has relatively higher amounts of nitrogen that enter groundwater (Tomich et al., 2015).

AD is already used extensively in California, primarily to treat MSS at wastewater treatment facilities and, in some cases, as dedicated facilities for energy production. The total mass of nutrients that can be recovered at WWTP could be increased by supplementing MSS with other waste streams such as OMSW, which had much larger nitrogen fluxes largely due to its higher gross mass and nitrogen mass concentration (Fig. 2, Table S22). Many of the existing anaerobic digesters that treat MSS have the capacity to treat additional organic waste beyond what is currently processed, thus efforts to utilize this existing infrastructure can increase the ability to recover nutrients (as well as energy) from other organic waste streams (Breunig et al., 2017). Additional work is needed to compare and spatially optimize the mass of recovered nutrients from existing digesters in California with the demand for nutrients in agricultural production, thereby effectively matching potential supply with existing demand that is currently met with synthetic fertilizers. Although we focused on nitrogen and phosphorus in this manuscript because they are the main constituents by mass in synthetic fertilizers and because their recovery could prevent eutrophication, the fate of other minerals such as potassium and calcium also merit further study. While fertilizer products produced via ammonia stripping or thermal distillation would not contain these minerals, potassium can be found in K-struvite and calcium often forms other precipitates with phosphorus.

The approach presented in this paper can be used to estimate the nutrient recovery potential from these five organic waste streams in other states and regions. For example, because 90% of California is sewered (Tomich et al., 2015) compared to 76% nationally (*Wastewater Treatment (% population connected)*, 2020), relatively more MSS is available in California than in other states. Likewise, California produces 21% of U.S. dairy commodities (Tomich et al., 2015) while only having 12% of the U.S. population, resulting in higher-than-average animal manure production (United States Census Bureau, 2020). California produces a representative percentage of U.S. agricultural value (13%) (California Department of Food and Agriculture, 2020) and food waste (15%) (Cal Recycle 2020; Environmental Protection Agency, 2020). However, nutrient mass concentration depends greatly on the sub-types of each organic waste stream (*e.g.*, dairy vs. poultry manure, almond vs. corn residue); therefore, analysis in other regions should consider the relative mass of the different sub-types of each organic waste stream.

One source of nutrients not considered for recovery in this analysis is liquid wastewater effluent. During wastewater treatment, only a portion of the nutrients are present in the MSS (15–40% of nitrogen, 28–94% of phosphorus) and many treatment plants still discharge the liquid effluents, and the nutrients present (4–85% of nitrogen, 6–72% of phosphorus) to the environment (unless the liquid effluents are utilized for irrigating crops) (Table S27). An alternative to recovering nutrients from this dilute wastewater would be to target urine, which is a concentrated waste stream that contributes the majority of nutrients to wastewater and is not currently used in other markets (Table S28). Notably, if urine was diverted and managed separately, the nutrient content in MSS would be expected to decrease.

We only explored one option for treating organic waste – AD. Many organic waste technologies are already established, such as slow pyrolysis, windrow composting, in-vessel composting, and vermicomposting, but these technologies likewise require careful analysis to verify system-wide impacts (Zabaleta et al., 2020). Other technologies are under development such as hydrothermal liquefaction and other fermentation pathways that could produce a wider range of end products besides biogas (Lohri et al., 2017). Most of these technologies are likely to produce a liquid stream with high nutrient content, therefore the analysis here still provides insight into the nutrient recovery potential.

The results from this research provide strong justification for continued development of nutrient recovery technologies and markets. Some technologies are well established from a technical standpoint, like ammonia stripping, but due to high cost and energy may not be feasible. Thus, continued innovation is warranted to further develop and scale-up technologies such as ion exchange and electrochemical stripping with lower cost, energy, and carbon footprints (Tarpeh et al., 2018; Kavvada et al., 2017). Other technologies, like struvite precipitation, are being implemented at full scale but need further refinement. A useful finding from this research is that each organic waste stream has a unique mass concentration of nutrients, total solids percentage, and N:P molar ratio, which is relevant for informing further technology development. The nutrient recovery percentage and the end products are technology- (and not context-) specific, whereas the mass and location of each organic waste stream are context-specific. The anaerobic digestion performance is also dependent on the characteristics of the input organic waste stream. Therefore, the quantitative analysis methodology presented here can be replicated in other contexts, modified as additional technologies are developed and refined, and be applied to characterize additional waste streams that are relevant in other contexts.

The recovered nutrients in this analysis are present as three different end products: liquid fertilizer (38% of TN), struvite (50% of TN, 66% of TP), and compost (12% of TN, 34% of TP) (% values are averages for all organic waste streams, processed by the baseline scenario). While compost is familiar and markets exist, there is still much uncertainty about how to develop markets for waste-derived liquid fertilizer and struvite (de Boer et al., 2018; Kok et al., 2018). Further efforts are needed to determine the environmental sustainability and life cycle costs for the presented digestate treatment systems as well as technologies reaching full scale. Additionally, efforts are needed in California and elsewhere to coordinate the use of these nutrients in agricultural production (EBMUD, 2017; Nkoa, 2014). Improvements in fertilizer use efficiency, such as better matching product assimilation rates to agricultural crops' nutrient needs, would reduce demand in California, and therefore increase the potential contribution of nutrient recovery from organic wastes to offset total market demand. Because crops typically utilize less than 50% of the synthetic nitrogen fertilizer applied, more than 50% of nitrogen enters the environment via groundwater, surface water, or air (Tomich et al., 2015). Improving fertilizer use efficiency would therefore also help close nutrient cycles by reducing the amount of nitrogen lost to groundwater and the air.

4. Conclusions

Anaerobic digestion is increasingly being used to treat a range of organic waste streams to produce energy; however, the nutrient-rich digestate must also be managed. In this study we quantified the mass of nutrients that can potentially be recovered from five key organic waste streams in California by integrating anaerobic digestion with nutrient recovery, and compared this mass to statewide fertilizer demand. In summary, for the high-market potential scenario:

- In 2020, municipal sewage sludge was the largest potential contributor to nitrogen and phosphorus recovery by mass.
- By 2050, other organic waste streams such as animal manure and agricultural crop residue increased in importance.
- The distribution of nutrients in the three different end products was: liquid fertilizer (38% of the total recovered mass of TN), struvite (50% TN, 66% TP), and compost (12% TN, 34% TP).
- AD facilities integrated with nutrient recovery could offset in-state synthetic fertilizer purchases by an estimated 11% of TN and 29% of TP.

Associated content

Supporting information available

Current organic waste management practices, mass concentration of nitrogen and phosphorus in five organic waste streams, percent recovery of nutrients during anaerobic digestion, percent recovery of nutrients through several separation processes flux of nitrogen and phosphorus from digestate through multiple liquid treatment and solid treatment processes, sensitivity analysis for recovery of nitrogen and phosphorus, mass of nutrients in produced fertilizers that would result from anaerobic digestion and nutrient treatment of the five different organic waste streams in the baseline high-market scenario in 2020 and 2050, mass in California of five organic waste streams.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.watres.2021.117717.

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