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Accelerating the Deployment of Anaerobic Digestion to Meet Zero Waste Goals

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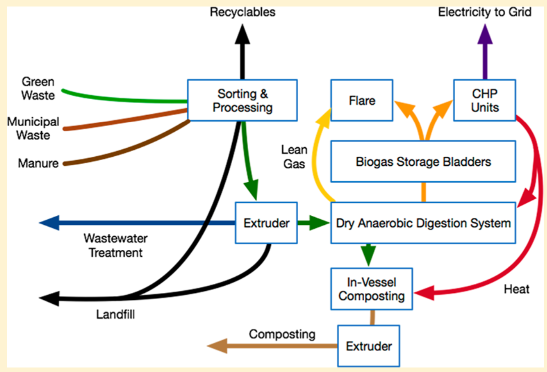
ABSTRACT: The U.S. places approximately 53% of its total municipal solid waste (MSW) in landfills, but state and local governments across the country are now setting ambitious environmental and waste diversion policies requiring, among other things, diversion and utilization of organics. Municipalities across the U.S. are employing anaerobic digestion (AD) as part of their strategy to divert organic MSW from landfills, produce biogas, and yield other beneficial coproducts such as compost and fertilizer. However, AD faces many technical, regulatory, and economic barriers to greater deployment, including upstream waste contamination, local odor and air pollution concerns, lengthy siting and permitting processes, and requirements and sizable costs for interconnecting to the electric grid. We identify a combination of scientific, operational, and policy advancements that are needed to address these barriers.



INTRODUCTION

The U.S. places well over half of its total organic municipal solid waste (MSW) in landfills. Of that amount, landfilled waste, food scraps, wood, yard trimmings, paper/paperboard, and cotton textiles contribute an average of 54% by mass.[1] Landfills occupy valuable land in urban areas and are the third largest source of methane emissions in the U.S.[2] The EPA Waste Reduction Model (WARM) tool estimates that, even in landfills with gas collection systems, about half of generated methane is captured.[3] Food waste, which is the largest contributor to total organic MSW, is particularly problematic from a climate change perspective because it biodegrades significantly faster than other waste types releasing methane more quickly into the atmosphere.[4]

State and local governments are setting ambitious environmental and waste management policies requiring greater diversion of organic MSW to energy-generating and composting facilities. Several states (e.g., California and Massachusetts) mandated 50% or more of MSW must be diverted from landfills by 2020. Several large U.S. cities established zero MSW policies (e.g., New York, San Jose, San Francisco, and Seattle). However, most states and municipalities are not on track to meet near-term goals and it remains an open question as to whether the aggressive long-term targets can be met. For example, achieving the 50% diversion by 2020 established in California's Senate Bill 1383 would require the state to more than double its organics processing capacity in just 18 months.[5] Lengthy siting and permitting requirements to mitigate air quality impacts and odor complaints, high capital and operational costs, utility interconnection costs and requirements, and uncertain revenue streams for coproducts all present significant barriers to diverting organic waste.[6]

Organic MSW is an inherently heterogeneous feedstock with value-added use options limited by technological, economic, or environmental barriers. Anaerobic digestion (AD) paired with composting appears to be one of the most promising uses of organic MSW in the near-term and will be crucial in diverting this waste. AD enables the conversion of organic MSW to biogas, electricity, and other beneficial coproducts including fertilizer and thermal energy. For example, California, one of the largest producers of landfill waste in the U.S., has significant potential for bioenergy, with 23.2 million tons of organic MSW per year that could be used to generate 13 TWh per year of technically available energy, or 4% of the state's total electricity consumption.[7,8] Despite this potential, only 2% of California's total generated MSW is currently being used for energy production—one percent dedicated to pyrolysis, incineration, biological conversion, or distillation and the other percent dedicated to waste tire-derived fuels.[9] Landfill gas recovery systems can be used to generate electricity as well;

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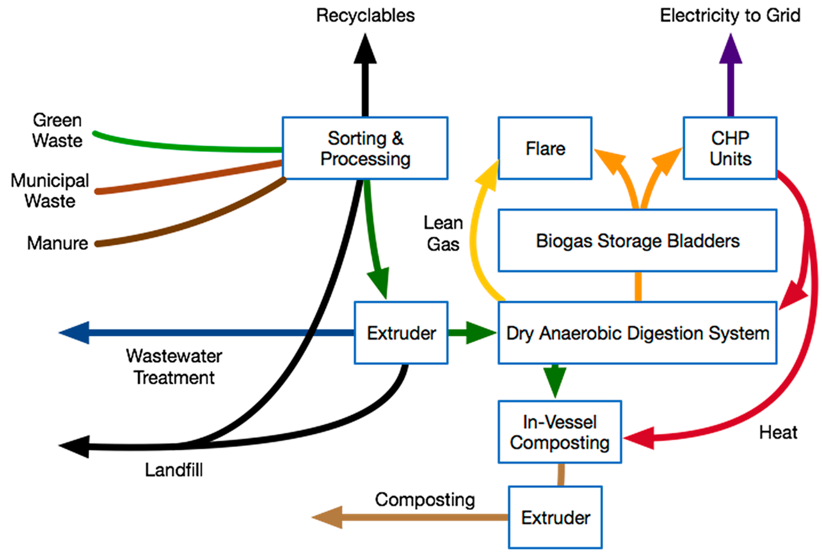

Figure 1. Simplified process flow diagram for ZWEDC dry anaerobic digestion facility.

total installed capacity in California is 555 MW, or 0.7% of the State's current overall generation capacity.[10] Anecdotally, we have observed that these systems may go down for long periods of time despite being reported as operational, so official estimates are likely to be skewed. The fraction of MSW used for energy generation in the U.S. is greater than in California, but still relatively low at 13%.[1]

In this paper, we identify a number of broadly applicable barriers standing between the current state of waste management and the aggressive waste diversion goals set across the U.S. We discuss the research needs posed by each challenge, and how they can be addressed by researchers studying waste collection and handling technologies, biological conversion strategies, waste diversion policies, and life-cycle cost and environmental assessments. There are five major challenges addressed here: (1) sorting technologies and practices to minimize feedstock contamination; (2) predicting biogas yields and composition from mixed waste streams; (3) mitigating air pollution to comply with local regulations and avoid odor complaints; (4) maximizing the economic value of energy outputs; and (5) maximizing the net climate benefits of AD and coproducts. We supplement findings from literature with our experiences working directly with the Zero Waste Energy Development Company (ZWEDC) in San Jose, California—one of the largest dry AD facilities currently operating in the U.S. (see simplified facility configuration shown in Figure 1).

KEY CHALLENGE #1: SORTING TECHNOLOGIES AND PRACTICES TO MINIMIZE FEEDSTOCK CONTAMINATION

Organic waste streams, including wastewater, food waste, green waste, and manure serves as feedstock for AD facilities. The nitrogen content, volatile solids content, average particle size, and degree of inorganic contamination in waste streams can determine the operational efficacy of an AD facility. Dry AD typically operates at 20% to >40% total solids (TS) (in comparison to <10% to 20% TS for wet AD) and offers more flexibility in the range of acceptable feedstocks, shorter retention times, and lower water use.[11] Dry AD's reduced water footprint (namely, that fresh water is not required to dilute solid organic waste streams) may make it particularly attractive for water-constrained regions with intense competition among water demands, including much of California, and its flexibility means it can process organic MSW streams with limited sorting and polishing steps. That said, preprocessed organic MSW can contain surprisingly high levels of inorganic contamination that pose a challenge for all AD facilities. Of the approximately 110 000 tons accepted by ZWEDC in 2016, 25−40% were inorganic residuals that were subsequently sorted (to some degree, by hand), removed, and disposed in landfills.

To reduce inorganic contamination, cities (e.g., San Jose), where the majority of the waste comes from, use a source-separation strategy (wet−dry bin, in which the wet bin is reserved for food scraps, food-soiled paper products, and landscape trimmings, while the dry bin is for all other waste), still resulting in an average 21% inorganic contamination.[12] Another dry AD facility in the San Francisco Bay Area, South San Francisco Scavenger Company (SSFSC), reported that hand sorting was adequate to deal with "very clean" organics sourced from residential locations, but when they began accepting commercial organics, they found these to be contaminated on the order of 30%, and required installation of depackaging and sorting equipment.[13] Screening out inorganics has associated labor, equipment, and energy costs, and tipping fees associated with landfilling the residual tonnage. Although dry AD facilities can handle larger fractions of inorganics, they still require the solid digestate to be screened for residuals before being sold as finished compost.

Mechanical screening equipment (e.g., trommel screens) are most commonly used to remove inorganics by particle size and extruders separate the liquid fraction. This equipment is suitable for typical liquid or small-particle size wastes accepted for wet digestion, but is likely to perform poorly on mixed waste more suitable for dry AD because the waste streams may contain whole produce and other large components.[14] Improving technologies and infrastructure specifically aimed at organics separation, including pretreatment and size reduction (both mechanical and biological) can help solve the problem. Strategies for reducing inorganics in waste delivered to AD facilities is also critical; there are still no reliable, agreed-upon guidelines for selecting between multi-

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stream and commingled collection systems, and the energy and cost estimates of different preprocessing and screening equipment is scarce. Future research should focus on tools and methods for determining optimal systems, based on the characteristics of communities and their waste streams, to help stakeholders make more informed choices.

Current material recovery technologies and infrastructure are optimized for throughput of high-value recyclables, such as aluminum, dry paper, polyethylene, and high-density polyethylene plastics using commingled collection systems and material recovery facilities.[15,16] Commingled collections systems are particularly problematic for facilities that rely on clean organic waste streams as they must incur significant processing costs. For example, Lakhan's economic analysis of 233 municipal processing systems in Ontario, Canada found that, although collection costs were 3% lower for commingled collections systems, processing costs were 49% higher for commingled collections compared to multistream collections.[17] Similarly, Zhuang et al. found the multistream collection pilot program in Hangzhou, China to be cost-effective by having greater savings in processing costs than increases in collection costs relative to conventional, commingled collection.[18]

KEY CHALLENGE #2: PREDICTING BIOGAS YIELDS AND COMPOSITION FROM MIXED WASTE STREAMS

In the United States, biogas has the potential to replace natural gas consumption by as much as 5% and 56% in the electric power and transportation sector, respectively.[19] For dry AD facilities, utilizing this production potential depends largely on the quality of organic waste feedstock. Depending on the terms of their contract, facilities may have little control over the sources of feedstock, and regulations dictate that waste be processed in a timely manner (e.g., within 48 h). As noted earlier, facilities often receive low-quality organic waste feedstock, negatively impacting their operational capacity, biogas production, and compost quality. For example, between January 2016 and December 2017, ZWEDC's biogas production fluctuated significantly, in some cases increasing or decreasing by more than 30% on a monthly basis.

Bolzonella et al. compared source-separated MSW with mechanically separated solid waste (mixed with gray wastes and sludge) and found that, on a per-kg volatile solids basis, the methane yield was 3.5 times higher for the source-separated waste.[20] This indicates that, even after feedstocks have been converted to volatile solid mass, the resulting biogas yield can vary dramatically. Biogas production also depends on the feedstock mix and carbon-to-nitrogen ratio. For example, the biogas yield of food waste is generally much higher than green waste, and yields can vary significantly across specific food types.[21,22] Maintaining an optimal blend of feedstocks may be infeasible for some facilities because they lack control over the timing and quantity of waste stream deliveries. To minimize variations in organic loading and spikes in digester gas production the wet AD facility owned and operated by East Bay Municipal Utility District (EBMUD) mixes incoming wastes in blending tanks.[23] Even for facilities that can exercise control, optimizing for biogas yield is a challenge for dry digesters. Using feedstock composition to predict biogas yield and composition is difficult because of the diverse community of microbes present in digesters, feedstock heterogeneity, variability in feedstock particle sizes, and mass transfer limitations within the digesters. Most metabolic modeling work focuses on individual hosts and pathways, although recent work has expanded to attempt to simulate the interactions within microbial communities.[24−26]

The International Water Association (IWA) Anaerobic Digestion Modeling Task Group was formed in 1997 to develop a generalized AD kinetic model.[27] Anaerobic Digestion Model 1 (ADM1) is designed to simulate wet anaerobic digesters. This approach is sufficient for simulating wastewater treatment facilities (WWTFs) under typical operations or with codigestion of high-moisture organic waste. Predicting biogas yield and composition in dry digesters is significantly more challenging because feedstocks are not a well-mixed slurry, and literature on predictive models for biogas yields and kinetics in dry AD systems is sparse. Improved methods for estimating biogas yield and quality for dry digesters, through a combination of analytical and empirical approaches, are greatly needed. Studying the microbial communities in digesters under thermophilic and mesophilic conditions, and exploring how those communities shift over time and space within the digesters, may offer valuable insights for optimizing biogas yields and preventing upsets. Preprocessing methods for dry digesters that can achieve improved feedstock mixing to minimize localized effects could make predicting and managing biogas production more tractable.

KEY CHALLENGE #3: MITIGATING AIR POLLUTION TO COMPLY WITH LOCAL REGULATIONS AND AVOID ODOR COMPLAINTS

AD and composting facilities have many air pollutant sources. Examples at ZWEDC include the indoor waste processing receiving area, anaerobic digesters, in-vessel and outdoor composting areas, flue gas from biogas-fired reciprocating engines or turbines, biogas flare, biogas storage bladder vents, and the transport of raw and processed waste to and from the facility.

These sources can emit pollutants to the atmosphere including criteria air pollutants (nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon monoxide (CO), and particulate matter (PM)), air toxics (hydrogen sulfide (H_2S), ammonia (NH_3), and organic compounds including formaldehyde), odorous compounds (NH_3, H_2S and other sulfides, and a number of organic compounds), and climate forcing species (carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and black carbon (BC)). In addition to their direct effects, NH_3, organic compounds, and NO_x are important precursors for other criteria air pollutants (ozone and PM). AD facility operations are constrained by air permits that set maximum allowable emission rates and specify operational parameter ranges intended to ensure the efficacy of emission control technologies. When AD facilities are out of compliance with their air permit, the local air quality agency may levy citations that carry monetary penalties, or they may be shutdown. Additionally, odor complaints have emerged as a major concern for AD/composting facility operators that have led to forced stoppage of certain operations (e.g., outdoor composting) and even facility closure.[28]

At ZWEDC, a set of relatively standard technologies are in place to limit harmful emissions. To mitigate odorous and other emissions from the waste receiving hall, the doors are kept closed whenever possible and the area is under negative pressure. The gases produced during anaerobic digestion are

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described as being either rich gas with a CH_4 content greater than 20% or lean gas with a CH_4 content between 3% and 20%. Rich biogas is collected in a bladder, sent to an iron sponge to remove H_2S followed by a carbon bed to remove sulfur, and finally is burned in a combined heat and power (CHP) system. The biogas-fired engine exhaust is treated with oxidation catalysts to remove CO and volatile organic compounds (VOCs) by converting them to CO_2. The exhaust is further treated by a selective catalytic reduction system to mitigate NO_x. The lean gas is mixed with rich gas and burned in a flare after it is scrubbed of NH_3. If engine capacity is inadequate to handle biogas production levels (e.g., an engine is down), additional rich gas is flared. The ultralean gas with CH_4 content less than 3% is treated with the acid scrubbers and biofilters to remove organics and H_2S. Initial composting occurs within in-vessel composting tunnels immediately following digestion. In-vessel emissions are treated with an acid scrubber and the biofilter to remove NH_3 and other reduced state compounds. Remaining solids are trucked to an off-site composting facility where material is composted in outdoor windrows.

Odorous emissions at the facility and during composting are particularly challenging to plan for and mitigate because they are the result of a diverse set of feedstock- and process-dependent compounds, and are not robustly regulated or quantitatively incorporated into Environmental Impact Statements. The same is true for composting facilities. Even when complaints are registered from the community, attribution of odors to specific sources can be challenging. Accurate characterization of odor sources and emissions is critical to odor regulation and management[29] and especially important for AD (wet and dry) facilities treating the MSW organic fractions that are often sited closer to densely populated areas than facilities processing agricultural wastes.[30]

The local air quality management district issued several notices of violation to ZWEDC for failure to comply with its operating permit during the first couple of years of operation. Violations included a series of temperature excursions and a failed source test of NO_x emissions at the enclosed flare, operation of the acid scrubber outside of the required pH range, failure to conduct an annual test of ammonia and organic compounds emitted from the biofilter, and operation of unpermitted emission sources. Both the air quality agency and facility agree that these excursions can largely be attributed to unplanned operating problems during the learning phase of such a complex and novel facility.

Improvements in odor dispersion modeling can inform regulated odor emissions levels and provide guidance to regulators on impact criteria. Dispersion models incorporate scientific understanding of atmospheric chemical and physical processes that relate emissions to ambient ground level odor concentrations (e.g., see review by Capelli et al.[31]). There are no standardized protocols for odor modeling and the application of odor dispersion modeling using models like AERMOD[32] to simulate surface concentrations at hourly intervals. Input parameters like highly time-resolved emissions and meteorological conditions and peak scaling methodologies need to be determined to capture the appropriate time scales (e.g., a few seconds to minutes) pertinent to human perceptions of odor.[33,34]

Due to the emerging nature of the dry AD technology and its short operational history, particularly in the U.S., both operational data (e.g., feedstock types and mixtures, biogas utilization strategies, aerobic digestate treatment) and emission measurements and estimation methods are limited. Variable feedstock and irregular facility operation (e.g., flaring due to CHP engine maintenance) imply that quantifying representative emission rates may require long-term monitoring. The large scale of operations (e.g., 100 m long composting windrows) and the complexity of emissions abatement equipment (e.g., large biofiltration basins that require careful moisture control) pose a challenge for both facility operators to maintain steady performance and researchers to measure representative emission rates. Research is needed to quantify emission rates of pollutants to comprehensively evaluate their impact on climate forcing relative to competing strategies (e.g., direct composting) and to provide necessary inputs to odor and air quality assessments.

KEY CHALLENGE #4: MAXIMIZING THE ECONOMIC VALUE OF ENERGY OUTPUTS

AD facilities' primary product is biogas, a mixture of approximately 50−60% CH_4 and 40−50% CO_2 and various trace contaminants. The facilities may also produce a range of coproducts including compost, fertilizer, and even biochar. AD facilities, especially those utilizing organic MSW as their primary feedstock, typically do not receive the majority of their revenues from selling energy and coproducts; instead, the vast majority of revenues come from tipping fees.[35] Although relying on tipping fees, which are typically set in long-term contracts, provides financial stability, it may not align the financial incentives with the greatest societal benefits. Facilities are motivated to accept and process as much organic MSW as their capacity allows to recover the large capital outlays, while the financial incentives to maximize energy and other products (e.g., fertilizer, compost) output are small. To prevent facilities from accepting waste at a premium and landfilling a large fraction, contracts generally limit the fraction of incoming tonnage that can ultimately be landfilled.

Enabling the sale of electricity from biogas powered generation sources (e.g., CHP) is largely constrained by economic challenges. The interconnection standards governing technical and contractual terms between generating system owners (i.e., AD facility in this case) and the utility are generally established by state utility regulators and can pose a costly and complex barrier.[36] Interconnection procedures and requirements may delay project development and add significant expenses to complete technical analyses, even more so in the case of newer technologies and applications. Bioenergy feed-in-tariff (FiT) programs are meant to guarantee small-scale bioenergy facilities attractive fixed-price standard contracts with utilities, and can be effective.[37] ZWEDC was the first facility to successfully enroll in California's BioMAT FiT program, which provides electricity price compensation to waste-derived electricity generators at about $130/MWh, significantly above current wholesale electricity market prices (e.g., $30-$40/MWh). While FiT programs have largely been successful, they present implementation challenges for policy-makers and utilities. FiT programs tend to be somewhat broadly defined in terms of the resources they support and may result in less cost-effective siting of projects on the grid if the program does not incentivize project locations near load centers.[38] In the case of BioMAT, facilities may only have 5 MW of total nameplate electric generating capacity and deliver no more than 3 MW to the utility's grid. This precludes larger

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AD facilities from participating and may discourage successful facilities from scaling up.

An alternative to burning biogas on-site for electricity generation is upgrading the gas to biomethane, which requires removal of CO_2, moisture, and trace contaminants. The biomethane can then be injected into pipelines as renewable natural gas (RNG) or used as fuel in compressed natural gas (CNG) vehicles. Gas upgrading also enables pressurized storage, which is otherwise costly and results in significant corrosion problems with raw biogas. Unfortunately, the best-available upgrading equipment is costly ($5.50−11.50 per 1000 scf of biomethane[39]), requires sophisticated controls and operators, and results in significant methane losses, or a combination of all three.[40] For comparison, average prices for delivered residential natural gas in the U.S. varied between $9.33 and $18.32 per 1000 scf.[41]

Once upgraded, pipeline injection has potential long-term advantages: rather than competing for subsidies with other low-cost renewables such as solar, RNG can be sold to gas-consumers in the same way renewable "green" electricity is sold at a premium, if policy supports are adopted. The success of upgrading will hinge on either a loosening of currently restrictive standards for pipeline injection or improvements in gas separation technology. Currently, the California Public Utilities Commission requires biomethane to meet the same 990 btus/scf standard as natural gas and approach nondetected levels for siloxanes.[42] If a facility produces RNG for vehicles, market connections are critical. Some facilities self-consume RNG as fuel for their own trucking fleets,[43,44] whereas others may enter partnerships to guarantee consistent RNG demand. Facilities that do not operate or have access to vehicle fleets are unlikely to generate consistent revenues. Uncertainty surrounding future RNG policy supports, including the Federal Renewable Fuel Standard and California's Low Carbon Fuel Standard programs, make the economic attractiveness of RNG under any scenario highly uncertain.

The research community will play a crucial role, both in improving biogas upgrading and separations technologies, and in providing owners and operators unbiased techno-economic and process engineering tools for selecting systems that best suit their particular biogas composition, scale, and desired specifications. For example, a diverse set of processes including pressurized water scrubbing, amine swing adsorption, pressure swing adsorption, temperature swing adsorption, cryogenic separation, and membrane technologies have all been developed for biogas separation.[45] Membrane technologies, in particular, may see improvements due to increased research activities in the application of metal organic frameworks, graphene, and ionic liquids for gas separation. Systems-level innovations will also be important; recent findings indicate that hybrid systems combining one or more membranes with another process may achieve lower costs and improved CH_4 recovery.[45]

■ KEY CHALLENGE #5: MAXIMIZING THE NET CLIMATE BENEFITS OF ANAEROBIC DIGESTION AND COPRODUCTS

Identifying the quantitative benefits of AD facilities remains incomplete, and the environmental benefits have not been systematically valued and incorporated into financial incentive designs.[46] Existing literature strongly suggests that both conversion to energy and composting are preferable to landfilling organic waste.[47,48] From a greenhouse gas perspective, the avoided landfill methane emissions far outweigh most, if not all, other emissions sources. For example, Murphy and Power[48] found that any strategy avoiding landfilling organic waste could save 1555 kg CO_{2e}/tonne of waste, whereas the avoided emissions associated with energy production were an order of magnitude smaller, ranging from 103 to 179 kg CO_{2e}/tonne of waste. The results suggest that energy-producing applications have a slight advantage in this particular study (1403−1479 CO_{2e}/tonne of waste compared to 1190 CO_{2e}/tonne for composting), but important data gaps remain. The net climate benefits of landfill CH_4 emission avoidance can be eroded by fugitive emissions of CH_4 from an AD facility, venting biogas to avoid over pressurizing storage bladders,[49] lack of CHP capacity, and species emitted with even higher global warming potential (GWP), such as nitrous oxide (GWP_{100} ∼ 300[50]) from the facility or composting operations, and possible black carbon (GWP_{100} ∼ 900[51]) flare emissions. Furthermore, no papers have documented greenhouse gas emissions associated with composting post-AD digestate relative to composting wet organic waste. The two composting processes are treated as having identical emissions, and this is likely to overestimate the emissions from digestate composting emissions. Comparisons for other emissions, such NH_3, H_2S, and nonmethane VOCs are also insufficiently explored in the literature. A better understanding of the life-cycle differences in air pollutant emissions and pollutant formation will be important in ensuring environmental quality, protecting human health, and achieving public acceptance.

Digestate value lies in its potential to increase net carbon sequestration to soils and offset demands for carbon-intensive nitrogenous fertilizers in agriculture and landscaping applications. Existing studies focus largely on digestate produced from clean streams, such as pig and cow manure, dairy waste, or slaughterhouse waste.[52] Even in these cases, the nitrogen content can vary by ∼20%, and application only during the growing season is crucial to prevent nutrient leaching, NH_3 emissions, excessive N_2O emissions, and runoff into ground and surface waters.[52,53] If nitrogen contents vary too much, it may lead farmers and landscapers to overapply, leading again to nutrient leaching and emissions of NH_3 and N_2O. Solid digestate from processes that make use of mixed feedstocks tends to be less attractive for composting than cleaner materials. For example, EBMUD digestate may be used as a soil amendment during the dry summer months, but is sent to a landfill as alternative daily cover during the wet winter months when land application restrictions are in effect.[23] Wastewater treatment facilities that make use of excess capacity by codigesting food waste with municipal wastewater solids face more stringent restrictions on their use of biosolids than those that do not.[54]

Without policy supports tied to carbon and fertilizer offsets, compost simply does not generate sufficient value to cover its costs, despite its potential for climate benefits and fertilizer demand reduction. Therefore, compost facilities generally charge a tipping fee that is on par with landfill fees.[55] This expense is then passed up to digester facilities that must pay the tipping fee to compost their solid digestate, which is the case for ZWEDC, SSFSC, and Monterey Regional Waste Management District's digester.[43] Providing incentives for landowners to apply compost on degraded lands, to restore soil carbon and increase water-holding capacity could improve utilization of residual solids. Any such policies must be

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informed by conducting measurements required for quantifying the net environmental impacts of applying compost. Lower-cost batch-by-batch characterization of nutrient contents could also help landowners better adjust fertilizer applications when supplemented with digestate or compost.

■ DISCUSSION

Reducing the fraction of organic waste landfilled in the United States is critically important to reduce emissions of potent greenhouse gases, avoid unnecessary use of valuable urban land, and recover energy and nutrients. Addressing the five challenges discussed above will require a combination of research and technology development, evolution of regulatory policies, and financial incentives that are aligned with the benefits most valued by society. A recurring theme is the need to place greater value on recovery and utilization of organic waste, and shift from tipping-fee driven throughput incentives to incentives based on environmental benefits. To achieve these fundamental shifts in how organic waste is valued and managed, further research is needed to quantify the variations in bioenergy production potential for different waste types, and the net energy and economic trade-offs of different process configurations and waste utilization strategies, including electricity generation and RNG.

Additional research, also of critical importance, is required to understand the emissions impacts of AD compared to competing options, and ensure that AD facilities are able to conform consistently to regulatory emissions standards and permits. Air permitting agencies will require that emissions from AD and composting will not contribute to exceedances, so improved strategies for predicting, monitoring, and mitigating emissions for a range of unconventional pollutant sources will be of high priority. The same is true for greenhouse gas emissions because climate change mitigation is a primary motivation for diverting organic waste. Future research must focus on understanding the drivers of CH_4 and N_2O emissions from competing organic waste management and waste-to-energy systems, and developing strategies to maximize net greenhouse gas benefits. Cross disciplinary research, operational improvements, and advancements in the structure of regulatory policies and financial incentives will play a role in meeting ambitious waste diversion goals across the U.S. and realizing the societal benefits of waste-to-energy systems.

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Notes

The authors declare no competing financial interest.

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