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EDITORIAL

The role of clean technology research in creating sustainable urban food waste solutions

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In the next 30 years, global population living in urban areas is expected to double, a trajectory expected to create new social, economic, and environmental challenges, and new opportunities to leverage urban systems research towards sustainability outcomes (Ramaswami et al. 2018). Food is at the heart of this issue. Urban populations will require a safe, stable, and nutritious food supply, yet urban food supply chains are expensive, inefficient, resource-intense, and ecologically damaging at local and global scales. Food production currently leads to significant demands on energy, water, and nutrients and emits pollutants to vulnerable ecosystems and greenhouse gas emissions leading to global climate change. Yet 30–50% of food produced from these resources is never consumed (Fig. 1), due to crop losses, post-harvest spoilage, wasteful commercial practices, and losses at the consumer scale. Globally, food losses and wastes across the supply chain are estimated at 1.3 billion tons per year (Gustavsson et al. 2011).

These losses present two challenges to future sustainability of urban systems: First, food does not reach the urban populations where it is most needed, and second, food waste management leads to environmental impacts that ripple across cities and surrounding rural regions. Urban food waste is primarily handled by landfilling, which leads to added expenses, energy use, and greenhouse gas emissions, particularly methane, which is released from anaerobic degradation of organic waste in landfills (Gunders 2017). Food waste management magnifies impacts from urban water and wastewater treatment and the transportation infrastructure used for waste collection and hauling. Even though 70% of food globally is consumed by urban populations (FAO 2017), the associated ecological, health, and economic impacts are shared by the rural systems where food is produced and where waste is often disposed.

Much of the urban food waste stream is not "waste," but is actually edible food that could be used to alleviate food insecurity. Novel technologies and community interventions have been launched to "rescue" excess food in some urban areas, as demonstrated in the recent surge in electronic apps intended to connect organizations with excess food to those in need. However, there is difficulty scaling up these initiatives and overcoming the mismatch between the business needs of food donors and the nutritional needs of receiving populations. Energy and resources embedded in wasted foods can also be recovered via composting or anaerobic digestion, yet there are steep economic and technical hurdles to widespread adoption of these pathways and of the many novel food waste valorization technologies that are rapidly emerging. I shared perspectives on these food waste challenges in an editorial previously published in this journal (Babbitt 2017). Here, I focus on specific issues and research needs that can advance food waste solutions specific to urban systems. An emphasis on the urban scale has two motivations. First, transforming urban food supply chains can create multiple sustainability benefits at a tremendous scale, given the anticipated growth of urban regions. Second, food systems are a compelling system through which poorly understood urban system interactions can be studied. Transforming urban food systems will require parallel innovations in energy infrastructure, transportation, buildings, water systems, governance, education, community initiatives, and business models.

Exploring these opportunities was the theme of a recent workshop on the topic of "Urban food waste solutions from farm-to-fork." Funded by the National Science Foundation (Award # 1929881), the event brought together researchers, policymakers, non-profits, small businesses, and industry representatives from across the USA to collaboratively identify critical research questions surrounding urban food waste solutions. The workshop outcomes identified multiple

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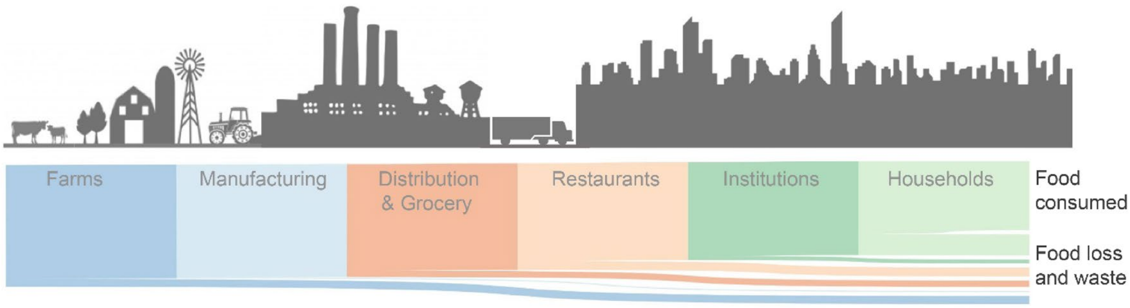

Fig. 1 Food loss and waste along the urban food supply chain, from "farm-to-fork" (data adapted from Gunders 2017)

research priorities for advancing knowledge (Babbitt et al. 2019), but I will highlight here three themes that I found to be most relevant to readers of *Clean Technologies and Environmental Policy*:

Research to create and deploy technology solutions appropriate for the urban scale

Currently, many of the incumbent technologies for growing and harvesting food and valorizing food waste are not scaled for urban deployment. In the case of production systems, food travels into urban regions from surrounding rural areas, whereas food waste management requires large-scale collection and hauling to distant composting or anaerobic digestion facilities, often centralized in rural areas outside the city. Novel urban-scale, decentralized solutions are beginning to emerge. For food production, an example is "urban agriculture," which often includes community gardens and vertical, rooftop, and indoor farms, like ones made from used shipping containers (Fig. 2). For food waste management, novel approaches include micro-hauling networks that use bicycle or low emission vehicles for waste collection and on-site food waste treatment and pre-treatment systems that use chemical, biological, or thermal treatment to reduce the mass, volume, or odour of food to minimize the required frequency of collection.

These decentralized solutions are effectively scaled for deployment in congested, space-constrained urban areas and provide co-benefits of job creation, entrepreneurial opportunities, and local self-reliance. However, they also face a steep path to widespread adoption due to competition with entrenched centralized systems that often offer an initial lower cost. Opportunities for research to bridge this gap include creation and validation of technologies that can operate economically at a smaller scale, investigation of policy and economic instruments that allow niches for decentralized efforts to find footing, and systems optimization to determine the most effective food production and waste management "ecosystem" that combines both traditional and emerging decentralized technologies (see Fig. 3) for maximum sustainability benefits.

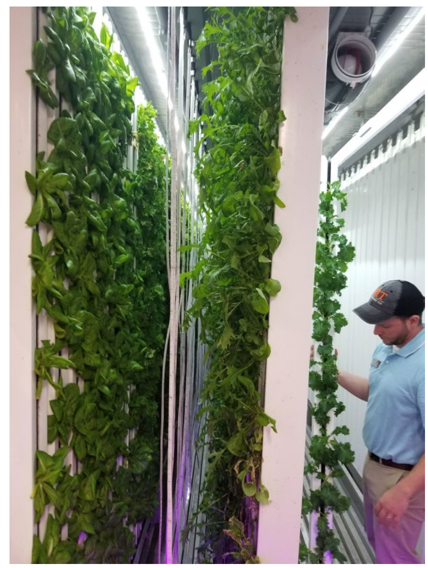

Fig. 2 A "farm-in-a-box" urban agriculture system that converts used shipping containers into vertical, controlled environment growing systems. Photographed by Callie Babbitt

Research to optimize waste valorization pathways for local conditions, feedstocks, and markets

Every urban area will have a unique food waste profile, varying in the amount, characteristics, and timing of food waste generation according to urban scale, geography, demographics, economic activities, and cultural influences. The technologies best suited to managing this waste stream will also vary, according to local or regional policy, existing infrastructure, siting restrictions, and cultural attitudes (e.g., "not in my backyard" sentiments). The co-products recovered from food waste valorization will also vary with the technology used or the markets and policy

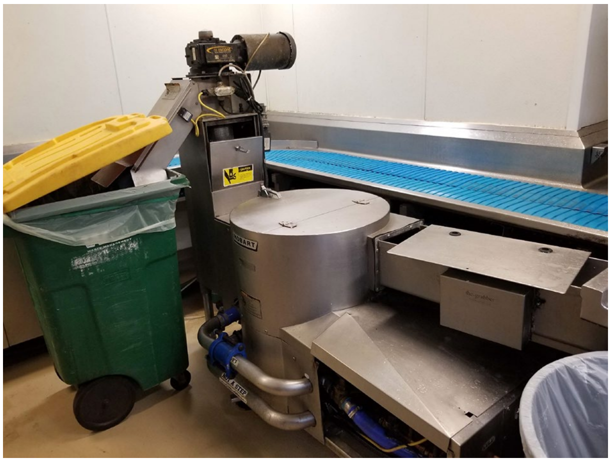

Fig. 3 Example of interacting decentralized and centralized waste management systems: an urban university cafeteria using a food waste pulper to remove water (and associated weight) from food waste to minimize cost and impacts of hauling residual wastes to a rural anaerobic digester. Photographed by Callie Babbitt

incentives or barriers in different regions. For example, anaerobic digestion generates biogas that can be used to produce electricity or that can be cleaned and compressed to use as a transportation fuel. A facility's choice between these two options will vary based on their business model, wholesale electricity price, local electricity and fuel demand, climate and renewable energy policy incentives, among other local factors. Further, some feedstocks may be ideal for anaerobic digestion, while others are better suited for thermochemical treatment (e.g., pyrolysis), composting, or conversion to animal feed. The resulting mix of product alternatives could possibly include syngas, biochar, speciality chemicals, fertilizers, compost, and other energy and bio-based products.

In every urban region, these hyper-local sources of variability create a conundrum for decision makers trying to determine the best technology pathway for a specific waste. Solving this challenge will require experimental demonstration and validation of new technologies and economic, environmental, policy, and social analyses of alternate pathways. In addition, each waste pathway also has the potential to generate waste of its own, as seen in the anaerobic digestion example, which generates a nutrient dense liquid digestate effluent stream. In some regions, digestate may be contained in covered lagoons, while in others, open-pond storage can lead to downstream emissions to air and water. By-products like digestate can be further valorized through additional treatment steps, but there is significant opportunity to study optimal downstream treatment and material management pathways and how these alternatives impact the recommended waste diversion pathway.

Research on critical enablers, barriers, and interacting systems

The research opportunities described above are necessary for advancing innovative solutions for reducing food loss and managing food waste. But, actually implementing such solutions in practice will require broader consideration of how new technologies interact with legacy urban infrastructure and how to leverage enabling systems to overcome technical, political, social, and economic barriers. Take the issue of policy as an example. A growing number of states and municipalities have enacted food loss and waste regulations, but it remains unclear how science can inform policy alternatives that reflect cost, efficacy, and trade-offs across the spectrum of different intervention approaches. Existing food waste policy is a combination of mandatory and voluntary mechanisms and takes the goals of both preventing and managing food losses and wastes. In addition, the interaction of policies related to food and food waste remains under study, even though there are significant interdependencies among food policy (food safety, agricultural subsidies), energy and climate policy (carbon and renewable energy credits), water policy (non-point source discharges, wastewater treatment), and local regulations governing the operation of businesses and waste infrastructure within a given urban region.

Another key enabler is the availability of high-quality, actionable data. Actors in the food supply chain have incomplete information about food loss and waste being generated or the specific costs and impacts of its management. Policymakers lack information about the capacity to rescue or recycle food within a given urban region, which may lead to overambitious diversion targets. Food rescue systems (including both donors and recipients) only have partial information about the others' needs, such as nutritional content of excess food and dietary needs and cultural preferences. As pointed out in my past editorial on food waste (Babbitt 2017), technology studies are often published without complete data about the physical and chemical properties of feedstock being treated relative to the performance of a specific valorization pathway. For all the potential solutions explored, the field lacks a shared set of metrics to calculate benefits and trade-offs and the data with which to make these comparisons. There is also interesting potential in new data collection approaches, such as crowdsourced citizen science that can generate information while also educating the public on food system sustainability.

Urban food waste systems also interact across different infrastructure systems, including energy production and transmission, transportation, built environment, water supply, and wastewater treatment, among others. Food waste systems intersect with a wide array of other technologies. One key example is that of food packaging, which has both the potential to reduce food waste by extending shelf life and preventing spoilage and the potential to enter the food waste stream as a contaminant that confounds downstream management. Polymer-based packaging is particularly a challenge due to the associated impacts of plastic pollution. Food waste and packaging are often researched as separate, isolated systems, although there is great potential in co-investigating how new innovations can provide solutions to challenges arising from both domains. Further, the role of consumer attitudes and preferences is often ignored in clean technology research, but consumers may have an intuitive view of packaging as inherently environmentally unfriendly, which can lead to purchasing choices with unanticipated consequences. This research domain will require systems analysis methods (e.g., life cycle assessment) and consumer behaviour and choice analyses in complement to technological studies.

While these are just a small sample of findings from the workshop, I view these themes as critical research questions towards which contributors to *Clean Technologies and Environmental Policy* will be able to make significant advances. These themes also represent an exciting opportunity for integrating knowledge across multiple disciplines and between academia and stakeholders with deep applied knowledge of the food supply chain. While this approach of knowledge "convergence" is a departure from traditional research, the challenges it entails are worthwhile in light of the benefits that successful research can achieve. If new knowledge leads to transformation of the urban food system, outcomes will include fewer food losses, improved public health, and reduced environmental and economic costs of food waste management. These outcomes will pave the way towards a secure, sustainable food supply capable of sustaining urban populations today and in the future.

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