



Transforming wasted food will require systemic and sustainable infrastructure innovations

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Currently, 40% of food produced in the U.S. is never eaten, leading to lost resources, economic costs, decreased food security, and the wasted food itself, which has immense climate and ecological impacts. However, unwanted food can be leveraged towards sustainability aims by, for example, diverting high-quality surplus to food-insecure communities, recycling carbon and nutrients into agricultural production, and converting food wastes into bioenergy. This transformation will require co-evolution of both *physical infrastructure* systems that produce, deliver, and manage food and waste and *human infrastructure*, from front-line workers to governance and institutions. This contribution will synthesize current knowledge and research in support of this transition, drawing from recent literature and two NSF-funded workshops on wasted food management in sustainable urban systems.

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Introduction

A safe, sustainable, and nutritious food supply is essential to population health and well-being. But modern food systems and their physical, human, and information infrastructures often fall short: they are expensive, resource-

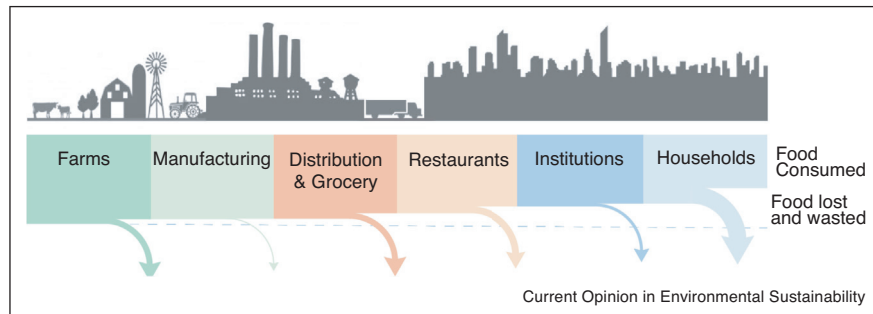
intense [1,2], and create ecological damages [3–5] and climate change impacts [6]. One in 10 Americans (and one in four globally) reported food insecurity [7], even before COVID-19, which caused unprecedented disruptions leading to food shortages, insecurity [8], and waste [9,10^{*}]. Food system infrastructures are also vulnerable to climate change [11], natural disasters, geopolitical instability, cyberthreats, contamination [12], and global health crises, underscoring the need to enhance food system resilience [13^{*},14–16].

Food systems are also wasteful, with 30–50% of food produced never being consumed [17]. Food is lost and wasted across the supply chain (Figure 1), from farms, processors, restaurants, groceries, and households [18,19]. The wasted food itself is a complex organic waste stream whose management can strain often aging and overloaded waste, wastewater, transport, and energy infrastructures. In the U.S., wasted food is typically landfilled, leading to methane emissions and climate impacts [20,21]. Globally, wasted food accounts for 8% of all greenhouse gas emissions — more than the entire airline industry [22^{*}].

While wasted food reflects inefficient food production and consumption practices, it also represents an opportunity for environmental, economic, and social gains. It can be re-envisioned as a resource by recovering carbon and nutrients from crop loss back into agricultural production; consuming more of what is purchased; diverting high-quality surplus to food-insecure communities; and converting wastes into bio-products and energy. Realizing this transformation is challenging, due to the food system's complex web of activities and actors that interact to produce, process, transport, consume, and waste nutritious substances [24]. Past efforts to minimize or manage waste have often met limited success because they fail to consider economic, social, policy, technology, and environmental interconnections inherent to this system [25^{**}].

We argue that without enhancing the infrastructure systems comprising food supply chains, efforts to address wasted food will not achieve intended sustainability and resilience co-benefits. New research and solutions are needed to address the physical infrastructure systems that produce, deliver, and manage food and waste; the human infrastructure, from front-line workers to governance and institutions; and the information infrastructure that enhances coordination and management [26]. As a

Figure 1



Food lost and wasted along the food supply chain, from 'farm-to-fork'. Arrow size corresponds to estimated flows of food consumed, lost, or wasted [23]. Graphic by Liz Sisk.

step towards such a research agenda, two workshops funded by the U.S. National Science Foundation were held on the topic of wasted food solutions [27,28]. This article synthesizes the workshop findings with nascent literature, to present knowledge and practice gaps we must address to realize resilient and sustainable food systems.

A framework for food system transformations

A circular framework for food production and wasted food management (Figure 2) offers a compelling alternative to inefficient and vulnerable linear food systems. Circular economy decouples economic growth from resource extraction and waste generation, and involves the interconnected strategies of narrowing, slowing, and closing resource loops [29,30,31]:

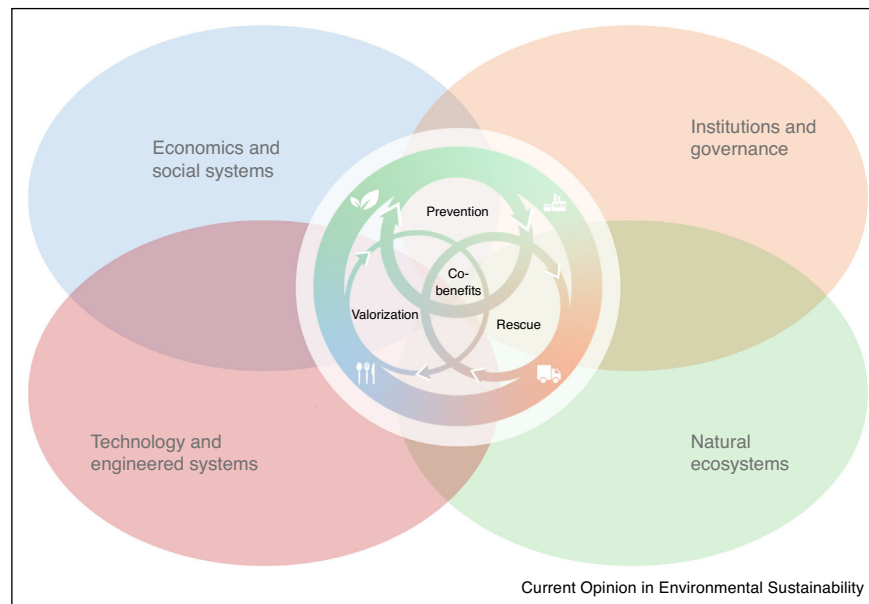
- Narrowing resource loops refers to using resource-efficient processes that fulfill societal needs but demand less net resource input per unit of economic output [32]. In food systems, these strategies reduce overproduction and ensure food reaches a consumer, thus preventing wasted food.
- Slowing resource loops refers to retaining the use and value of materials for as long as possible [33]. In food systems, this approach can enhance resilience and retain nutritional value by rescuing surplus food before it becomes waste. Ideally, this surplus would feed people, but where food deviates from nutritional, cultural, or practical needs of consumers, it can be down-cycled for animal feed.
- Closing resource loops involves recovering an end-of-life resource and returning it to productive use [34]. Closed-loop material flows take inspiration from cycling of nutrients and energy in nature, where waste from one organism becomes 'food' for another [35,36]. These processes are often termed 'valorization' because they convert waste into higher-value resources

by recovering energy, carbon, nitrogen, phosphorus, and water.

Collectively, circular strategies can provide sustainability benefits spanning the food system, including improved diets [37], particularly among the food insecure [38]; reduced food system resources and costs [39*]; reduced stress on waste treatment systems [40]; enhanced urban agriculture practices [41]; increased generation of renewable energy [42]; improved health for workers and communities near waste management sites [43,44]; and enhanced food system resilience to shocks [13*]. Circular economy also offers a more holistic perspective than conventional waste management frameworks, which is particularly important due to the resource-intensive nature of food systems and the potential for significant sustainability benefits from upstream interventions that prevent food loss in the first place [45,46].

While the benefits are clear, the pathway to implementing circular economy strategies is complicated; current estimates suggest just over 3% of food is recaptured and just over 30% recycled annually in the U.S. [47]. The next sections synthesize literature and discuss future research outlooks on the human and physical infrastructure systems at the heart of these interactions. Here, physical (or 'human-built') infrastructure includes all technological and engineered systems required for food systems to function and maintain quality of life, including energy and water provisioning, solid waste and wastewater management, transportation, and the built environment. The term 'human infrastructure' became more widespread in U.S. discourse with the Biden Administration's infrastructure policy goals [48], referring to workforce capacity and human needs. We use the term more narrowly to focus on people, governance, institutions, and sociocultural and market forces addressing wasted food. Lastly, we discuss 'computational and data infrastructures' that facilitate food's transformation and allow

Figure 2



Circular economy framework for wasted food, depicting intersections and co-benefits between prevention, rescue, and valorization and between the food system's social, natural, technological, and governance systems.

us to model systemic interconnections and analyze outcomes.

Physical infrastructure systems

At the core of food system infrastructure are the processes involved in food production, manufacturing, packaging, transportation, and distribution, which are collectively responsible for over 100 million tons of wasted food each year [19]. At the farm scale, some degree of food loss may actually prevent downstream waste, by removing and re-tilling food with defects that may spoil during handling or be rejected and landfilled by consumers [49,50]. Beyond these losses, further wastes can be minimized by extending harvest [51], relaxing cosmetic standards [52], creating economically viable routes for farmers to donate or recover excess [53], and innovating technologies that can improve overall efficiency through sustainable agricultural intensification [54] or precision agriculture [55,56]. In developing economies, loss reduction hinges on basic infrastructure improvements in roads, post-harvest storage, and information exchanges between farms and local markets [57]. Recently, advances in controlled environment agriculture, including hydroponic, vertical, and rooftop gardens and novel greenhouse systems, have been suggested as a means to minimize waste during production [58,59]. However, a critical research need is proactive evaluation of such solutions to ensure that they can feasibly be scaled to meet demand and do not create

unintended economic or environmental impacts compared to conventional agriculture [60,61].

Food is a widely transported commodity, and packaging and distribution play key roles in reducing losses and enabling downstream loop-closing approaches. Food packaging is necessary to prevent spoilage and maximize shelf life, but may itself add other sustainability concerns [62,63]. Once packaging has served its role in the food supply chain, it usually becomes an added waste to manage or a contaminant in downstream food waste treatment. One opportunity is to consider packaging and edible material as parts of one integrated food system, opening new research directions regarding design of polymers that are durable during transport and distribution but then can degrade at the same time scale and within the same processes as the food scraps with which they are commingled [64,65,66]. However, despite recent advances in degradable bioplastics, broader research is required to understand their suitability for treatment in existing composting and anaerobic digestion infrastructure [67,68] and to evaluate consumer food safety for novel materials and applications.

Transport infrastructure is a critical component of all three circular economy approaches for wasted food. Market forces and the dynamic urban landscape have resulted in locations with limited grocery store access, forcing consumers to make tradeoffs between location,

affordability, and quality of food [69], possibly limiting broader adoption of prevention and rescue strategies. Transportation is also central to downstream management of surplus and wasted food, which typically involves source separation followed by transportation and distribution (for food rescue) or transportation, pre-treatment, conversion, and distribution of the biofuels, energy, or other products ultimately recovered (for valorization) [70]. Food pickup and routing can be particularly difficult in urban settings characterized by congestion and narrow streets. Advances in logistics and systems design will be critical to improving efficiency. For example, many food rescue business models leverage digital platforms to create micro-networks used to collect and redistribute food [71]. Emerging businesses in this space are often small, and models for upscaling and partnering can address inefficient transportation and logistics [72] or establish networks of sufficient size to make food waste hauling economically viable [73].

Even with expanded efforts to narrow and slow food system resource loops, some waste will be inevitable, requiring significant expansion of waste management infrastructure [74]. This infrastructure must be resilient to variability in wasted food composition [75] and generation volume [76,77]. Siting new food waste recovery facilities must balance competing objectives, including local regulations, transport costs, revenue sources, public opinion, environmental justice and equity concerns, and downstream systems to treat residual organic waste after the primary conversion process [70,78]. A central challenge is ‘matching’ the heterogeneous food waste stream to the valorization technology and associated infrastructure that can recover the most value with the lowest economic cost and environmental impact [79]. The aim is twofold: creating products that displace fossil fuel-derived chemicals or energy sources, while also diverting food waste from landfills [80,81]. Revenues for firms operating waste-to-value systems arise both from charging tipping fees to food waste generators and from selling the produced electricity, natural gas, or bio-products [74,82].

Waste-to-infrastructure matching is challenging because some feedstocks are better suited for incumbent technologies, such as anaerobic digestion or composting, while others are ideal for emerging processes, such as thermochemical treatment [83] or conversion to high value chemicals [84]. For example, relatively dry waste (<30% moisture) can be converted at much higher energy efficiency via gasification or pyrolysis [85,86]. The resulting mix of products from valorization may include syngas, biochar, specialty chemicals [87], fertilizers [88], compost, biofuels, electricity, or other bio-based products. A choice among these options will be governed by the firm’s business model, social goals, market prices for co-products, local electricity and fuel demand, and climate and

renewable energy policy incentives and targets [89,90]. One emerging opportunity is for integration across technologies to create food waste ‘biorefineries’ that convert multiple incoming feedstocks into varied co-products [91,92]. This model may provide economic benefits to firms, particularly in response to fluctuating product demand and prices [93,94]. Further research is needed to investigate the technical performance of food waste valorization pathways and the environmental, economic, and social tradeoffs between alternatives [95,96].

Technology choice and infrastructure siting also introduce new interdependencies between critical regional infrastructures, but their interconnections have not been exploited for benefit when it comes to wasted food. The interactions of food and waste with broader regional infrastructures, such as energy, water, and transportation, can help identify hot spots where these linkages represent vulnerabilities to system resilience [97] and opportunities for joint interventions for cost-effective resource savings [98,99], along with accounting for cascading effects between infrastructures [100]. Thus, the interdependencies of waste systems with regional infrastructures that are currently seen as vulnerabilities can become targets of opportunity.

Human infrastructure systems

Transforming the food system through innovations in human infrastructure means shifting the capacities, incentives, and default actions that lead to poor waste prevention and management. While we focus here on humans’ infrastructural role as consumer and worker, humans are, of course, more than infrastructure. The multi-dimensionality of people’s lives beyond this role is core to the challenges and opportunities we consider, in consumer behavior, industry practice and policy, educational institutions, and the workforce.

With about 37% of U.S. wasted food directly attributable to decisions made by consumers in their homes and another 29% in retail and foodservice [47], the human infrastructure shaping consumer behavior is ripe for transformation. A 2020 National Academies of Science, Engineering and Medicine report adopts a systems framework for understanding consumer food waste causes and solutions, and recommends pathways for transforming human infrastructure to reduce waste in the United States [25], while highlighting a significant research gap in intervention evaluation. While the report focuses on the U.S., findings are applicable for other high income countries.

One pathway focuses on directly changing behavior by addressing consumer motivation, ability and opportunity to reduce waste [101,102], including via a customizable Federal platform for behavior change campaigns. This pathway acknowledges the importance of cultural and educational infrastructures in amplifying behavior change

[103,104], with media influencers increasingly shaping social norms. A second pathway suggests changes to policy and industry practice that support consumers to make less wasteful decisions. For example, food date labels have been implicated as a cause of wasted food [17,105]; the National Academies report recommended parties work towards Federal harmonization of date labels with accompanying education programs [106]. Outside government policy, many commercial food enterprises are increasingly engaged with broad voluntary sustainability certification programs [107]. Realizing these transformations, however, will require parallel research on efficacious and scalable waste reduction interventions [108] and new technologies that support reduction and redirection of wasted food.

The education sector is a critical enabler of the pathways discussed above and a cornerstone of human infrastructure, with nearly 140 000 primary, secondary and post-secondary educational institutions in the U.S. [109] poised to address wasted food through schools' triple role of educating, socializing, and feeding students. Schools generate tremendous food waste due to the volume of meals served (29+ million US children in 2019 [110]), children's preferences, food quality, and the ways meals are implemented [111]. Food waste education in schools can shape a generation's behaviors and attitudes through developing food and food waste literacy at a time of plasticity when lifelong behavioral patterns are established, as well as contributing to current household practices [25]. Particular benefit may come from linking the classroom and cafeteria [112,113]. Several school food waste interventions have shown potential, including classroom and teacher education [114]; engaging students in intervention design [115]; and using nudges to shift portion size [116]. Suggestive evidence exists for other types of interventions, including tracking and communicating about waste through audits [113], improving meal quality [117,118], and scheduling recess before lunch [119]. Overcoming the barriers to broader adoption of these approaches will require research in two main domains: well-designed studies to clarify what interventions work, and in what context, and to test at scale; and research to quantify co-benefits on critical outcomes, including cost savings, educational alignment, and staff burden.

The food waste human infrastructure comprises nearly 22 million workers in the U.S. alone, many of whom are contracted rather than directly employed [120], plus an additional large group of waste management workers in governmental and private settings. Workers engage in food waste prevention and management through both direct job roles and indirect opportunities that arise or which can be created with sufficient motivation, opportunity, and ability to take action. While the chance to 'do good' through work cannot substitute for sufficient pay or

good working conditions, it may enhance feelings of pride and improve workplace climate [121]. Intervention research suggests engagement is a valuable strategy for addressing waste of food [25]. While addressing waste can benefit workers, it also carries risks. In some food and waste management sectors, injury and illness rates exceed twice the national average, while workers in waste management, truck transportation, and waste collection have fatalities four to eleven times the US average [44].

Several challenges limit the transformations needed. First, there is virtually no research on worker engagement to address waste of food. Second, formative studies suggest that workers and their managers often differently perceive protocols, challenges, and opportunities for addressing food waste [121], but given the low level of workforce power and high turnover, managers may eschew worker input into responses. Employers often have low incentives to reduce workers' risks, due to low regulatory enforcement and absent standards, and opportunity to avoid legal responsibility for contract worker injuries [122]. Research needs include gaining insight directly from frontline workers to understand their perceptions of challenges, hazards, and specific strategies that could be adopted to improve waste prevention and management; piloting and testing worker-engaged interventions in a range of regional contexts and workplace types; and examining co-benefits and co-harms of interventions for workers, firms, and society, including spillover effects such as waste prevention in workers' personal lives. In particular, cost-benefit assessment may help make the case to employers to adopt interventions. Approaches and theories used in related fields such as medical errors and food safety should also be evaluated.

Computational and data infrastructures

Human and physical infrastructure systems give rise to complex interactions that are challenging to model or assess but important to capture to ensure that transformations lead to overall sustainability benefits and avoid unintended consequences. This challenge is further compounded by the lack of high quality data to characterize the magnitude and drivers of wasted food flows. This challenge presents an opportunity for research to expand and enrich computational infrastructures by leveraging advances in data science and modeling.

Food system data are often fragmented across case studies of varying scales from household to aggregate national food production and loss data. Existing data on wasted food in the US do not uniformly capture the full food system and are subject to significant variability in accounting method [39] and food flows [77] and reliance on self-reporting by consumers or organizations [123]. Interdisciplinary collaborations can expand and refine the toolbox of data collection approaches [124], while partnerships with governmental, commercial, and non-

governmental actors are needed to validate and visualize new data streams to facilitate decision making. Such efforts require an architecture supporting data harmonization to capture food system complexities [125*] in the context of wasted food.

Ideally such a data architecture would be flexible, multi-depth, and geo-referenced to facilitate multiscale analyses and model-building efforts. Flexibility is required as it must both store diverse qualitative and quantitative data types and content (waste quantities; nutrient and chemical compositions; technology specifications; economic, financial, environmental, and social outcomes) and enable data-driven research efforts. Geo-referencing enables regionalizing and localizing models and analyses and articulating spatial linkages and interactions. Multi-depth capabilities are crucial to integrate micro to macro data layers and accommodate different granularities. To ensure harmonization across data sources and facilitate modeling and assessment, relevant ontologies for food [126] and wasted food [127] must be expanded and linked to capture potential waste sinks (landfills, incinerators), prevention activities and outcomes (campaigns, intervention effect sizes), and circular material flows (rescue, valorization) embedded in the various infrastructure systems detailed above.

Even with these data advances, two main knowledge gaps still remain in computational modeling of wasted food in a circular economy context: explicitly representing the interactions within and beyond the food system and quantifying environmental, social, and health outcomes and tradeoffs that result from these interactions and potential solutions. Food systems and their interactions are often represented with input output models (I–O) [128*], computable general equilibrium (CGE) models [129], or within integrated assessment models (IAMs) [130]. While I–O models can provide bottom-up representations of exchanges between sectors, they are based on linear input-output matrices, and are aggregate and not granular to specific processes. Further, I–O models hold macroeconomic variables such as population change and economic growth as exogenous. CGE and IAMs are top-down models that study the economy as a whole, and can represent macroeconomic changes, but cannot represent detailed bottom-up processes such as agricultural production technologies, anaerobic digestion placement decisions, and transportation infrastructure.

Life cycle assessment (LCA) can be applied to create estimates of metrics relevant to sustainability, including cumulative emissions and damages that arise from the food supply chain processes and from food loss and waste [131*]. Historically, LCA research has used data-intense process models to characterize mass and energy flows associated with specific industry or infrastructure systems, but has less frequently captured economic [132] or social

[133*] outcomes. LCA can, however, be integrated with economic models of food system interactions using either I–O models (classified as ‘attributional’ because they describe a system as is) or CGEs (classified as ‘consequential’ because they model outcomes of a simulated change) [134–136]. One advantage of consequential LCA is the ability to quantify marginal impacts of complex system shifts through connected dual variables, thus capturing potential change in food systems after interventions [137]. Yet LCA still faces a number of challenges when applied to the food system, including the difficulty of drawing boundaries between coupled human and natural systems involved in food provisioning and the potential bias of valuation methods that prioritize efficiency over resilience and other desirable but difficult-to-measure sustainability attributes [138].

Thus, we need modeling advancements that can leverage both explicit process representation and marginal changes as a result of decisions or interventions. Studies can accomplish these goals by integrating the process representation of optimization models, the aggregation of I–O models, and the marginal, nonlinear representation of equilibrium models. Capturing the full spectrum of food system sustainability [139] will require both novel LCA approaches applied to circular economy solutions [140] and the integration of complementary methods that account for resilience and equity [138]. As an example, if food waste valorization via anaerobic digestion provides an energy source in a region, we could quantify systemic sustainability outcomes while accounting for both supply and demand changes in the energy sector [74]. Such advancement would allow flexibility to expand modeling capabilities to quantify uncertainty [141] or to further couple analyses with climate [142,143], hydrology [142,144], and integrated assessment models [145] as has been done with other sectors.

Conclusion and research outlook

A safe, sustainable, resilient food supply is a necessary facet of a sustainable future. Research described herein offers the potential to transform the food system by preventing or minimizing food loss, managing unavoidable food waste, and improving resilience, public health, equity and sustainability co-benefits. However, the solutions encompassed within the circular economy framework described here also face broad challenges to adoption. One such challenge is the complexity underlying the infrastructures that comprise the food system and their interactions across other technical, social, institutional, and ecological systems. Here, we propose that a transformational approach will involve identifying critical food system infrastructure components, testing interventions aimed at preventing, rescuing, or valorizing wasted food, and ultimately assessing the systems-level outcomes using advances in data science and modeling methods.

However, carrying out research to achieve these visions faces broader barriers. For example, identifying and testing human infrastructure solutions will require deep collaboration between academic researchers and food system stakeholders that go beyond traditional academic structures. Similarly, creating the data and models required to analyze physical infrastructure interactions will require collaboration across disparate fields and knowledge domains. The emerging domain of convergence science provides an approach to ‘holistically understand, create, and transform a system’ [146*] through team-based collaborations organized around complex societal challenges. Carrying out research within this framework offers a path to build generalizable insights that are transferable to other infrastructure systems and to realize a circular food system with less resource use and waste and greater benefits to societal health and well-being.

Conflict of interest statement

Nothing declared.

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This article introduces, defines, and comprehensively explains the emerging field of convergence science — a new holistic framework for addressing complex societal challenges that previous disciplinary approaches have not been able to fully comprehend.