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Systems engineering opportunities for agricultural and organic waste management in the food–water–energy nexus

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Managing food, water, and energy waste streams leads to more sustainable production, consumption, and distribution processes in the food–water–energy nexus (FWEN). Agricultural and organic waste streams within the FWEN can be difficult to manage due to both volume and their potential environmental impacts. However, they are also often characterized by a rich mix of organic compounds, ripe for conversion into energy or value-added products. Process systems engineering (PSE) stands uniquely positioned to understand the interconnections between food, water, and energy of agricultural and food wastes, wastewater, and municipal solid waste (MSW). Targeted advances in systems analysis as well as design and optimization of integrated FWEN waste management technologies and processes are expected to have the greatest impact. When building integrated mathematical models, care must be taken to consider waste treatment not as an independent process unaffected by the FWEN, but as a core component of the FWEN, connected to all nexus resources and systems.

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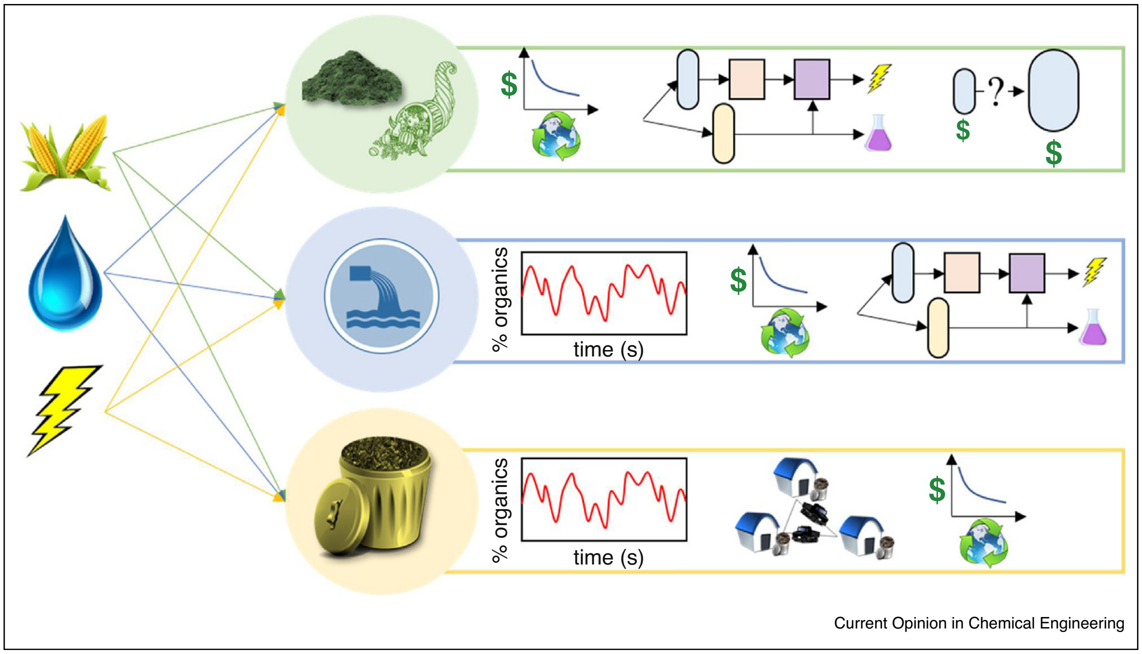
Introduction

The food–water–energy nexus (FWEN) concept, proposed in recent years, represents the interconnected production, distribution, and consumption processes of food, water, and energy [1•,2]. The concept has been used as a tool to address issues that arose from attempting to make food, water, and energy systems individually sustainable by instead providing a perspective that accounts for the inherently intertwined relationships among the three resources [1•]. The core principle is that it is impossible to produce, distribute, and consume one (food, water, or energy) without producing, distributing, or consuming the other two. Thus, wasting food, water, or energy wastes all three resources. In this paper, we discuss the issue of agricultural and organic waste as a core, understudied component of the FWEN, and we use the FWEN concept as a guide for sustainable design of integrated, simultaneous FWE production and waste processing.

In 2011, the Food and Agriculture Organization (FAO) of the United Nations estimated that approximately 33% of food produced for human consumption is wasted or lost [3,4]. Since 70% of global water withdrawn and 30% of global energy consumed is directed toward producing, processing, and consuming food, then wasting 33% of our food means wasting 23% of global water withdrawals and 10% of global energy consumption [1•]. Food production is also a source of enormous organic wastes. The world's market animals produce approximately 8 trillion kg of manure throughout their lifetimes, approximately double the mass of crude oil produced globally in 2015 [5–7]. Approximately 330 km^3/y of municipal wastewater, a significant fraction of which is food and other organic waste, is generated globally [8]. In 2012, the World Bank estimated that 1.3 billion kg of municipal solid waste (MSW) was created globally — much of it discarded food waste [9]. These waste streams within the FWEN may be viewed as undesirable streams to be managed or as streams with a rich mix of organic compounds that may be new sources of heat, power, and value-added products. Process systems engineering (PSE) stands uniquely positioned to pursue the latter view.

Many emerging waste management technologies that convert waste to energy or value-added products require advances in process design and integration. Advances in supply chain design and optimization can also streamline waste management and valorization within the FWEN, especially with wastewater and MSW. However, the management of these waste streams, when considered, is rarely done within the context of the FWEN, leaving opportunities for novel, integrated systems-based approaches underinvestigated. While PSE can play a significant role in readying these emerging technologies for commercial success, there are many research challenges to address. These waste streams often have unstable and varied compositions, and their production can be

Figure 1



The FWEN wastes considered in this paper and proposed PSE research challenges and opportunities to minimize/valorize each waste. Top — agricultural and organic wastes; middle — wastewater; bottom — MSW.

decentralized. Further, there are no general methodological frameworks that guide identification of optimal treatment/minimization strategies for waste within the context of the production and distribution processes within the FWEN. Detailed process models for treatment, minimization, or valorization of agricultural and organic wastes must first be built and then integrated with mathematical models for design and optimization of local and regional FWEN supply chains to fully capture the interconnections of waste management integration with FWEN systems and subsystems [1•,10•]. Figure 1 highlights each FWEN waste stream we consider in this paper and summarizes contributions the PSE community can make to minimize and/or valorize FWEN wastes.

This paper first reviews each of these waste streams in detail, highlights connections between them and the FWEN, and provides examples of emerging technologies for their management or valorization. Next, we present specific research challenges. Finally, we present possible PSE approaches to address these research challenges.

Agriculture and food production waste

Overview

There are two main types of organic waste that come from agricultural and food production systems: animal wastes and waste throughout the food supply chain. Much of this waste, such as animal manure, is unavoidable as long as there is demand for animal products. With increasing population and prosperity across the globe, food production is projected to increase dramatically, and with it, water and energy requirements [1•]. Indeed, global livestock inventory is expected to increase by up to 117% between 2000 and 2050 [11,12]. Currently, animal manure reaches coastal watersheds via surface runoff or by groundwater leaching, wasting significant amounts of nutrients, causing loss of habitat and biodiversity, and inducing eutrophication, algal blooms, and hypoxia [11]. Other unavoidable organic waste from livestock production include tendons, bones, lungs, skin, and blood, presenting unique environmental and health concerns if not handled properly [13,14].

Other wastes produced throughout the food supply chain however, could be avoidable [15]. In general, more food is wasted at the food production stage in developing countries, and more food is wasted at the consumption stage in developed countries [15]. Increasing population and shifting diet preferences also drive increases in waste. For example, demand for Greek yogurt has exploded in the U.S. to 25% of all yogurt sales [16•]. The waste streams from Greek yogurt production account for 2/3 of the input milk, and they are extremely difficult to process with traditional methods used for 'sweet' whey [17]. While this represents only one stream of global food waste, it is a burgeoning waste source for which there is currently no widely accepted treatment or management technique. Some proposed technologies for handling the problem