CHAPTER

Valorization of food processing by-products via biofuel production

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1. Introduction

The problem of food waste has become the focus of intense global scrutiny, because of the significant nutrient, energy, and water resources required to feed the world's growing population, and the environmental impacts associated with moving food materials from primary production to consumption or "farm-to-fork" (Fig. 4.1). Many governmental and nonprofit organizations have become active in addressing the seemingly absurd state of affairs in which 30% or more of food produced globally is never consumed by humans, whereas 27% of the human population suffers from some level of food insecurity (ReFED, 2016; Smith et al., 2017). Groups active

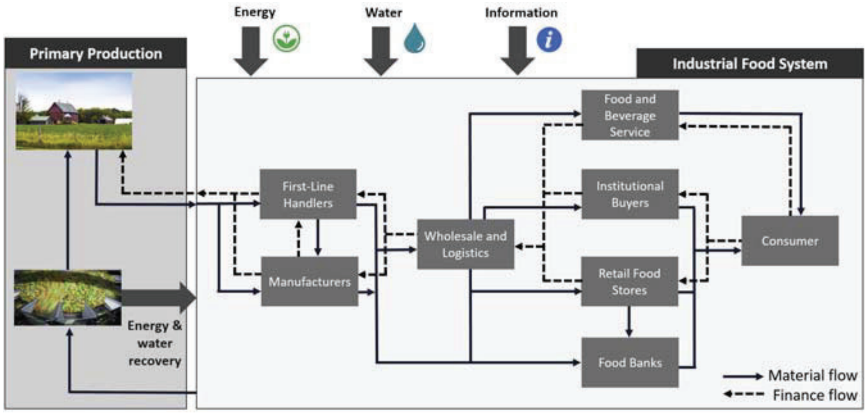

FIGURE 4.1

Material and finance flows in the global food system, also including critical inputs of energy, water, and information. Many opportunities exist for energy and water recovery that can benefit primary production and the industrial food system.

Adapted from National Research Council, 2015. A Framework for Assessing Effects of the Food System. National Academies Press.

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in promoting alternatives to conventional food waste treatment methods (landfills, wastewater treatment, incineration) include the European Institute of Innovation and Technology—Food (EIT Food) in the European Union, The Waste and Resources Action Programme (WRAP) in the United Kingdom, and Rethink Food Waste through Economics and Data (ReFED) in the United States, as well as the Food and Agriculture Organization (FAO) of the United Nations.

Different regions of the global food system have distinctly different profiles of food waste generation (Trabold et al., 2018). Generally speaking, developing economies experience more loss in the agriculture and primary production stages of the food supply chain, largely due to a lack of storage and transportation infrastructure. Conversely, more economically affluent regions generate the majority of their food waste near the consumption part of the supply chain. Food processing companies (or "Manufacturers" as indicated in Fig. 4.1) operate at the intersection between primary production and the industrial food system and, unlike most other stages, contribute a remarkably consistent fraction of total food waste generated (on a kcal basis) across all global regions (Lipinski et al., 2013):

- Industrialized Asia: 2%
- South and Southeast Asia: 4%
- North Africa, West and Central Asia: 4%
- Europe: 5%
- Latin America: 6%
- Sub-Saharan Africa: 7%
- North America and Oceania: 9%

These relatively modest waste generation fractions would seem to imply that food processing operations are efficient in how they utilize primary products from agricultural operations and prepare these materials for entry into the downstream supply chain, starting with wholesale and logistics. In this sense, other stakeholders across the global food system may benefit by better understanding how food waste is managed in processing plants that can maintain economic viability and competitiveness only if all system inputs and outputs are controlled, optimized, and valorized to the greatest possible extent.

Aside from the strong economic incentives driving efficient food processing operations, this stage benefits from two other important factors:

- Processing plants generally manufacture a small number of similar products, and thus, any waste produced is relatively homogeneous and contaminant-free.
- Waste is generated in a few locations at relatively large per-site rates, and this offers economies of scale for a variety of waste valorization strategies, such as those shown in Fig. 4.2.

Although many prior studies have documented the use of food processing wastes in animal feed, compost, and other value-added products (e.g., Lin et al., 2013), the focus of this chapter is on using these materials for biofuels production based on the technologies outlined in Section 2. Generally speaking, biofuels cannot provide as

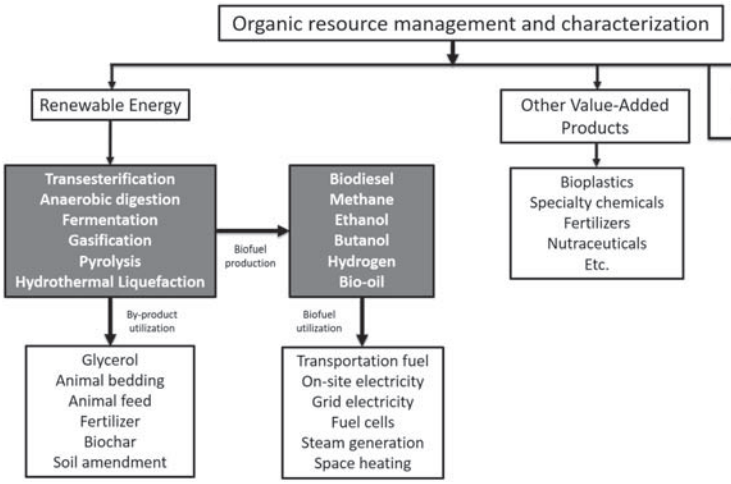


FIGURE 4.2

Flowchart of possible food waste valorization pathways, with biofuel production as a practical option for food processing wastes that are heterogeneous or contain contaminants, making them unsuitable for higher-value products such as nutraceuticals or animal feed.

great an economic rate of return (on a per kg waste basis) as many other value-added products but may have utility in cases where the organic matter is fairly dilute or generated at a relatively low volume, so combining it with other available waste resources makes economic sense. Upon mixing wastes with different properties, many of the higher-value valorization options are lost, but such combinations may serve quite well as biofuel feedstocks. In fact, biofuels are already produced from food waste on a massive scale around the world, mostly through the process of anaerobic digestion (AD) in landfills and wastewater treatment plants. These conventional waste management systems, however, are generally not efficient converters of the embodied energy present in food waste and, at least in the case of landfills, do not sufficiently capture the generated methane to avoid its deleterious impact on global warming. A much more economically and environmentally sustainable approach is to develop systems that intentionally collect and convert food waste to energy, thereby enabling the food processing waste generator to benefit from the material they invested in from the start.

2. Methods for production of biofuels from food processing by-products

As stated above, the production of biofuels from food processing wastes is not necessarily the most economically or environmentally sustainable option, and other valorization pathways may offer better return on investment to the waste generator. However, in many cases, biofuel production makes sense for waste streams with inconsistent physical and/or chemical properties, containing small amounts of impurities that render them unsuitable for upcycling to secondary food products for humans or animals, or are available in a diluted state making combination with other organic waste streams (e.g., dairy manure) the most practical strategy. Also, transportation logistics play a central role in determining when food waste-to-biofuel conversion is viable. For example, a food processing plant may elect to divert waste to an anaerobic digester located in close proximity, even with payment of a tipping fee, instead of taking on the development and management costs of converting the same material to a secondary food product that could generate another revenue stream. This outcome is often the case with smaller, regional facilities that do not have significant in-house research and development expertise, or lack the desire to expand beyond their core business areas.

In the following discussion, we present three main conversion technologies that have been previously applied to convert food processing wastes into biofuels:

- *AD* to produce hydrogen- or methane-rich biogas
- *Fermentation* to produce liquid alcohol fuels, such as ethanol and butanol, as well as hydrogen
- *Thermochemical conversion (TC)*, including gasification, pyrolysis, and hydrothermal liquefaction (HTL), to produce hydrogen-rich syngas and bio-oil

Transesterification is another widely used process to convert waste vegetable oil to fatty acid methyl esters, commonly known as biodiesel. However, because this technology typically uses a single feedstock material, it is not discussed in detail here and the reader is referred to available reference resources (e.g., Van Gerpen, 2005; Knothe et al., 2015). Beyond describing the three core technologies above and reviewing the recent literature relevant to this chapter, we do not consider whether or not the specific technology or process methodology has achieved commercial scale, nor do we consider the various ways in which the biofuels thus derived can be productively utilized for electricity generation, transportation fuel, combined heat and power (CHP), etc. The potential uses of by-products of biofuel production (e.g., glycerol, fertilizer, biochar) and different possible scales of operation are discussed in connection with the waste biorefinery concept in Section 3. It should be noted at the outset that there are a number of useful reference resources that have previously addressed various aspects of food waste valorization to biofuels, including Arvanitoyannis (2010), Chandrasekaran (2013), Kosseva and Webb (2013), de Jong and van Ommen (2014), and Trabold and Babbitt (2018).

2.1 Anaerobic digestion

AD is a multistep biochemical process whereby microorganisms break down degradable organic matter in the absence of oxygen. It is a common method for converting food waste into renewable biogas, composed mostly of methane (CH_4) and carbon dioxide (CO_2), combined with other minor constituents such as water vapor and hydrogen sulfide (H_2S) present in much smaller quantities.

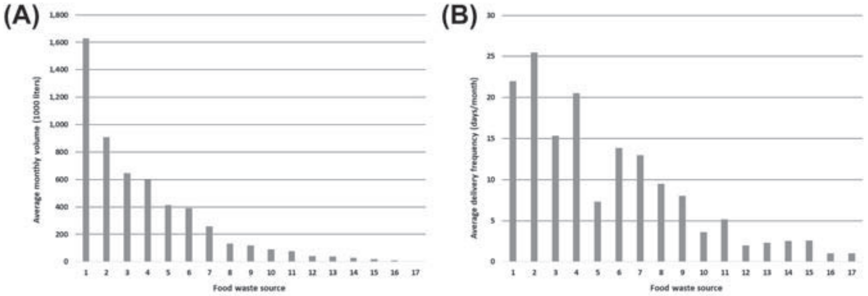
AD systems are deployed worldwide, from the scale of small family-sized systems numbering in the millions in China and India, up to very large industrial systems concentrated in Europe.

Because of the importance of AD as an industrial waste management technology, many papers have provided overviews of different system configurations, operating parameters, and biogas production potential of various food waste materials, including several reviews published in the past year: Labatut and Pronto (2018), Li et al. (2018), Ren et al. (2018), Xu et al. (2018). From these reviews, it is apparent that most of the published studies cover bench-scale experiments with volumes of 10 L or less and often do not comprehend key control parameters that are critical to operation at full scale, such as the organic loading rate (ORL, the quantity of digestible feedstock entering the AD reactor per unit time) and the carbon-to-nitrogen ratio (C/N) of combined feedstocks, the latter typically recommended to be controlled in the range of 20—30 (Labatut and Pronto, 2018). For a particular food waste material, a combination of various food waste materials, or food mixed with manure, the rate of biogas production would be expected to increase with increasing OLR up a certain optimal level dictated by the specific chemical and micronutrient properties of the substrates undergoing digestion. It is also apparent that the potential of AD as a sustainable food waste management strategy relies heavily on the specific types of food waste available. For example, based on the results of the study of Ebner et al. (2016) and further analysis by Labatut and Pronto (2018), the average volumes of biomethane produced (at standard temperature and pressure) by salad mixes, ice cream, spent coffee grounds and filters, and stale bakery products were 14, 55, 106, and 414 L of CH_4 per kg of waste, respectively. Generally, materials with high lipid and/or degradable carbohydrate contents produced the greatest amount of methane. Ebner et al. (2016) also showed that some wastes can be combined in a synergistic way to produce more biogas than can be generated by the same substrates processed individually, with up to a 20% enhancement when weighted on a volatile solids (VS) basis.

Despite the availability of extensive literature on the biomethane potential of a wide variety of food waste materials, in practice it is challenging to operate “pure food waste” digesters unless processing conditions are optimized for specific properties, OLR, hydraulic retention time (HRT), etc. (Fiore et al., 2016). In many regions, anaerobic codigestion (AcoD) is the preferred practice, whereby a stable primary substrate (such as dairy manure) is combined with mixed secondary substrates (including food wastes) that may vary significantly over time in regard to their chemical/physical properties and influent volumes. To achieve high ORL and maintain process stability, many AcoD plants operate with primary-to-secondary substrate ratios of 70:30 and usually not in excess of 50:50. Codigestion has the benefit of greatly enhancing biogas production for relatively low-energy substrates such as wastewater sludge or animal manure (Liu et al., 2016), and it has been reported that codigestion yields significant reductions in net greenhouse gas (GHG) emissions relative to conventional manure and food waste management practices (Ebner et al., 2015; Usack et al., 2018). In regard to AcoD plant operation, it is instructive to understand the actual profile of the types of food waste materials employed at commercial scale. As an example of data acquired from a large facility operating on a dairy farm in upstate New York with a 1.4-MW engine generator set, Fig. 4.3 shows average monthly waste volumes and delivery frequencies over a 6-month period for 17 industrial food system sources. The data reveal very large variations in the volumes of waste provided from individual entities, from over 1.6 million L/month to less than 4000 L/month, and delivery frequencies ranging from 26 to 1 per month. It is also important to note that all waste sources identified in Fig. 4.3 are in liquid or semiliquid phase and have few alternative valorization options available, such as composting that can be used for many solid phase pre- and postconsumer waste streams. The advantage of using liquid wastes is that there is minimal pretreatment (such as grinding) required to make the material suitable for pumping through the AD system.

2.2 Fermentation

Fermentation relates to a variety of biochemical processes facilitated by microbes (e.g., *Saccharomyces cerevisiae*), and in the context of this chapter, it is used to refer to processes generating fuels that can potentially be used for sustainable transportation or other energy conversion systems based on ethanol, butanol, and hydrogen. It is well known that ethanol is produced at very large scale using primarily corn in the United States, sugar cane in Brazil, and other dedicated energy crops in Europe and



(C)

Source	Description	Source	Description
1	Cheese process wash and over production	10	FOG from grease traps
2	Organic milk waste	11	Rice drink & rice yogurt production effluents
3	Dairy permeate, DAF and production waste	12	Syrup and sauce overproduction
4	FOG	13	Yellow grease from restaurants
5	Unsold skim and butter milk	14	FOG from grease traps
6	Dairy whey	15	FOG from grease traps
7	Whipped topping waste	16	FOG from grease traps
8	FOG from grease traps	17	FOG from grease traps
9	Yellow grease from restaurants		

*FOG = fats, oils and grease; DAF = dissolved air floatation

FIGURE 4.3

Representative average monthly inputs of food processing wastes to an anaerobic codigestion plant in New York State.

Asia. Although agricultural residues and other cellulosic resources are gaining a greater share of the feedstock mix, food processing wastes account for a very small fraction of the materials used for ethanol production, and facilities using food waste are generally much smaller than those using conventional commodity crops that often produce more than 100 million gallons/year (379 million liters/year). Using data from September 2018, *Ethanol Magazine* listed only six plants in the United States using crop residues or food waste streams for ethanol production[1]: DuPont Denisco (Nevada, IA, 114 MMLy); Merrick/Coors (Golden, CO, 11 MMLy); Parallel Products (Rancho Cucamonga, CA, 6 MMLy); Parallel Products (Louisville, KY, 23 MMLy); Poet (Emmetsburg, IA, 76 MMLy); and Summit Natural Energy (Cornelius, OR, 4 MMLy). Butanol is a four-carbon alcohol with several features that make it a potentially better transportation fuel and closer drop-in replacement for gasoline in internal combustion engines (ICEs). These features include higher energy content, lower vapor pressure, lower water miscibility, and lower corrosivity than ethanol (Harvey and Meylemans, 2011). Hydrogen fuel can also be produced by a number of different processes, with dark fermentation being the most commercially viable due to no requirement for external energy input or lighting and generally lower operating cost (Yasin et al., 2013; Łukajtis et al., 2018).

Recent papers by Hegde et al. (2018) and Hegde and Trabold (2018) have provided comprehensive reviews of published studies describing the use of food processing waste streams for production of ethanol, butanol, and hydrogen:

- Ethanol → bakery waste, waste potato mash, potato peels, sweet potato waste, apple pomace, grape pomace, tomato serum from sauce production, cheese whey permeate, pineapple, and banana peels
- Butanol → bakery waste, waste potato, wastewater from palm oil production, cheese whey, apple pomace, and acid whey
- Hydrogen → tofu processing wastewater, cheese whey, apple pomace, pineapple, banana, and mixed fruit peel waste

Between the two liquid fuels, ethanol yields are typically much higher than butanol, but in both cases, the measured alcohol production rates are generally below levels needed to achieve commercial viability. For ethanol, Hegde et al. (2018) showed that only high solids content materials such as waste bread, restaurant and cafeteria waste, and apple pomace can achieve the ~10% product concentration common in corn ethanol production. For butanol, a concentration of at least 1.5% is considered necessary to have any possibility for scale-up, based on the 2% maximum yields reported for batch fermentation with *Clostridium* strains. Similarly, a small subset of the investigated substrates was determined to be viable for conversion to butanol (only apple pomace and potato starch). Higher yields are possible, but only with a product recovery subsystem that would add processing

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[1] http://www.ethanolproducer.com/plants/listplants/US/Operational/All; MMLy = million liters per year.

costs. Although Hegde et al. (2018) suggested that nonfuel solvent alcohols may be higher value products for fermentation of food processing wastes, if energy is the desired outcome, AD (Section 2.1) may be a better option, especially for liquid-phase waste streams.

There may be more potential for the valorization of food processing wastes through the dark fermentation pathway for hydrogen production, because of the current interest in expanding options that move the industry away from conventional steam methane reforming. Using renewable hydrogen in fuel cell vehicles running at much high efficiencies than ICEs is a compelling objective, but much more work is needed to understand the compatibility and integration of food waste—derived hydrogen with proton exchange membrane fuel cell systems used for vehicle transport (del Campo et al., 2012; Rahman et al., 2015).

2.3 Thermochemical conversion

For solid-phase food processing waste streams with relatively low moisture content, TC is a potential valorization option. In the context of this chapter, TC refers to processes based on high-temperature treatment in the complete absence of oxygen (pyrolysis) or with less oxygen than the stoichiometric level needed for full combustion (gasification). Although TC technologies have been widely studied as a pathway for conversion of municipal solid waste (e.g., Sørum et al., 2001; Arena, 2012), there is relatively little research reported on quantifying energy production potential of food waste materials. A recent review article by Guran (2018) summarized studies of animal- and plant-based food materials that have been converted via TC methods, and showed the potential for the valorization of waste streams that may not be suitable for the biochemical technologies described above (Sections 2.1 and 2.2). Such challenging feedstocks include animal bones and carcasses, tree nut and coconut shells, and corncobs. In cases where the desired process output is solely biofuel for subsequent conversion to electrical and/or thermal energy (or vehicle fuel after further purification), gasification is the preferred pathway, because the primary process output is syngas comprised of about 85% hydrogen and carbon dioxide. Ahmed and Gupta (2010) evaluated pyrolysis and gasification using dog food as a model food waste material, and found that the latter provided significantly higher hydrogen yield, but required longer reaction time. Higher hydrogen yield can also be achieved by applying a secondary water-gas shift reaction stage ($CO + H_2O \rightarrow CO_2 + H_2$). However, the performance of a food waste-to-energy gasification process is significantly affected by the specific chemical and physical properties of the waste feedstock, including moisture and volatile matter content, bulk density and size, elemental composition, lower heating value (LHV), inorganic components (some of which can serve as catalysts), and other contaminants (N, S, Cl, etc.) that could result in undesired gas phase constituents (Zevenhoven-Onderwater et al., 2001). Because of the challenges associated with managing TC processes for food waste feedstocks that may vary greatly over time, “there are almost no gasification/pyrolysis processes that have been solely developed for food waste” (Pham et al., 2015).

Gasification is clearly the preferred technology in cases where syngas production is the most economically favorable process output, with only a small amount of ash generated as the other reaction product. On the other hand, pyrolysis has the advantage of providing three main value-added co-products (syngas, bio-oil and solid "char"), the relative quantities of which can be adjusted by judicious control of processing parameters. In *fast pyrolysis*, organic matter is rapidly heated to temperatures around 500°C and the resulting vapors are condensed to produce bio-oil, typically at a 60%−75% yield on a dry basis. A significant advantage of this approach is that the resulting high energy content liquid can be readily stored and transported, thereby decoupling the ultimate application from the production process. The bio-oil can be refined for use as transportation fuel, feedstock for electric power or steam generation, as well as for more advanced applications as raw materials in the production of fertilizers, building materials, phenolic compounds, etc. (Venderbosch and Prins, 2010). In *slow pyrolysis* the organic waste material is heated at a slower ramp rate, and the maximum temperature dictates the relative yields of syngas and solid char, comprised mostly of a very stable form carbon; in this process option bio-oil is typically not the desired product. Grycová et al. (2016) studied the pyrolysis generated syngas composition of several low moisture content waste materials (cereals and peanut crisps), and determined that hydrogen concentrations in excess of 60% were achieved for reaction temperatures in the range of 750−800°C. Lower temperatures may be favorable to increase the yield of char, which when intended for use in soil amendment, environmental management or similar applications is usually referred to as "biochar" (Xu et al., 2011; Lehmann and Joseph, 2015).

TC may be the preferred option when solid waste characteristics are known to vary greatly over time or if there is the possibility of small amounts of contamination that could adversely impact living organisms responsible for the fundamental biochemical processes in AD and fermentation systems. For example, pyrolysis may be suitable for "real-world" waste streams where it is impractical or cost prohibitive to separate food material from packaging. A number of recent studies have demonstrated the potential benefits of copyrolysis of food wastes and other biomass materials with common plastics such as low- and high-density polyethylene (LDPE and HDPE): Serio et al. (2008), Önal et al., (2012), Abnisa and Daud (2014), Dewangan et al. (2016), Hassan et al. (2016), Yang et al. (2016), Tang et al. (2018), Uzoejinwa et al. (2018).

Another related thermochemical technology that is not as well developed at large scale is hydrothermal liquefaction (HTL), involving processing biomass at moderate temperature (280−370°C) and high pressure (10−25 MPa) to produce a crude-like bio-oil (Toor et al., 2011). This method is particularly well suited for wet feedstocks, because there is no need for drying. However, the corrosive operating conditions require the use of high-cost components that increase the capital investment. Despite the challenges encountered to date in developing HTL to commercial viability, it would appear that there is significant future potential because the technology can be applied to many different waste streams beyond food processing waste, including primary and secondary wastewater sludge, animal manure, fats, oils, and grease. Based on the recent study by Skaggs et al. (2018), combining all of these materials available in the conterminous United States as feedstock for HTL could potentially meet 23.9% of the national demand for aviation kerosene fuel.

3. Food waste biorefineries

As outlined above, there have been many laboratory-scale studies of the conversion of food processing wastes into renewable biofuels, including methane, hydrogen, biodiesel, ethanol, and butanol. However, effectively producing these fuels at commercial scale and achieving economic competiveness with incumbent technologies without subsidies has been challenging to say the least. In the United States, disposal rates for landfills and wastewater treatment are relatively low, and there is ample supply of low-cost natural gas. Therefore, without acquiring a credit for the production of “green” energy, there is little economic incentive to do so. With the current global focus on climate change and the expected future environmental impacts, it is possible that, in the future, greater value will be attributed to avoiding fossil carbon emissions, but this depends on many economic, political, and social factors that are difficult to predict.

One approach proposed to enhancing the economic performance of food waste-to-energy systems is the application of the so-called biorefinery concept, whereby one or more feedstocks are converted into a variety of value-added coproducts with very little residue, akin to a petroleum refinery. As stated by Cherubini (2010), “Biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy.” Although using mostly food waste is possible in principle (Carmona-Cabello et al., 2018; Dahiya et al., 2018), to make such systems practical, it is probably necessary to look beyond just the waste produced by the various stages of the food system (Fig. 4.1) to other resources that are potentially much larger and more consistent over time, such as lawn and forest residues, solid waste and wastewater from households, and even algae and seaweed. At the scale of a large, centralized facility, it is conceivable that a wide variety of specialty chemicals, bioproducts, fertilizers, solid, liquid, and gaseous biofuels could be produced, but such biorefinery outcomes can be achieved by combining a smaller number of subsystems around a single primary conversion system. For example, there has recently been growing interest in combining AD with thermochemical methods to valorize the solid fraction of the effluent from AD (also called “digestate”) and also to potentially minimize the environmental impact of field spreading this stream (Opatakun et al., 2015; Peng and Pivato, 2017; Posmanik et al., 2017). Angenent et al. (2018) recommended enhancing the economic viability of AD by upgrading biogas into biomethane, converting carbon dioxide in biogas to more biomethane by hydrogenotrophic methanogenesis, generating cooling power from process heat, and producing bio-oil and a liquid biochemical product from organic matter. Perhaps the most compelling approach, albeit the farthest from commercial reality, would be to combine multiple technologies at a community scale where individual households, institutions, and businesses could extract value from the food and other organic wastes they generate, while maintaining investment and employment opportunities within the community itself (Fig. 4.4).

In developing potential biorefinery system architectures, it should be recognized that many opportunities exist for utilizing a single substrate (or associated coproducts) in more than one conversion system. For example, waste cooking oil (WCO) is a common precursor for biodiesel (via transesterification), but also has a very high biomethane potential of 641 L CH_4/kg (at STP), and thus is an excellent input for anaerobic codigestion (Labatut and Pronto, 2018). Apple processing waste (pomace) is an important food processing by-product generated worldwide and also in large quantities in our local region, because New York is the largest apple-producing state in the United States after Washington. This material has thus been widely studied in connection with various food waste-to-energy conversion processes, for example:

- Direct combustion of apple pomace can offset in-plant energy costs, but economic viability depends on waste flow rate, waste disposal cost, and fossil fuel price (Sargent et al., 1986).
- AD of apple slurry, waste, and pulp resulted in methane yields of 0.228–0.308 m^3/kg VS (Gunaseelan, 1997).
- Batch fermentation of apple pomace with *S. cerevisiae* at 5L working volume produced ethanol output of 0.4 g/g wet food waste (Parmar and Rupasinghe, 2013).

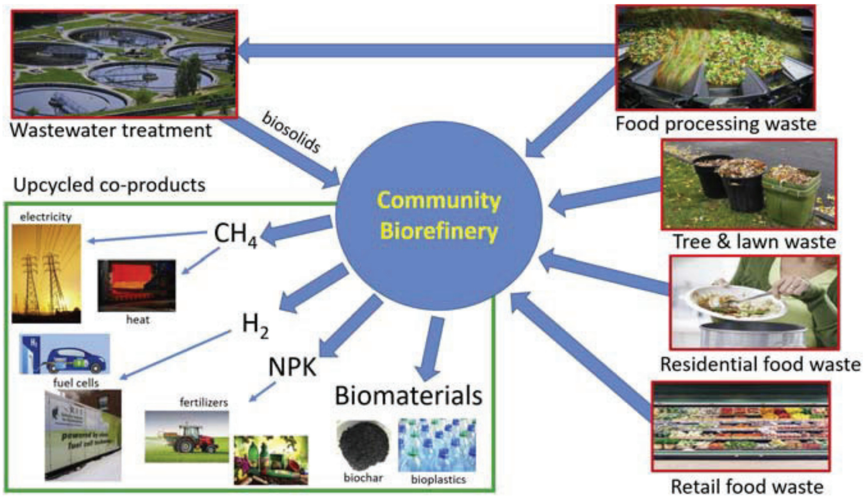

FIGURE 4.4

Conceptual community-scale biorefinery, with diverse materials (including food processing waste) combined to yield an array of value-added products.

- Apple pomace was used for butanol production with strains of *Clostridium acetobutylicum* and *Clostridium butylicum*. Yields of between 1.9% and 2.2% of fresh apple pomace were reported (Voget et al., 1985).
- Biohydrogen was produced via anaerobic fermentation of apple pomace with river sludge and achieved maximum cumulative yield of 101.08 mL/g total solid (TS) with an average H_2 production rate of 8.08 mL/g TS/h (Feng et al., 2010).
- Pyrolysis of apple pomace produced poor biochar yield but relatively high net energy output of coproducts of about 6 kJ/g of feedstock (Xu et al., 2011).

A similarly diverse collection of fundamental waste-to-energy studies exists for many common single-component food sector waste streams, including potato, coffee, tomato, etc., as well as mixed wastes from cafeterias, restaurants, etc.

One important consideration often overlooked in developing waste-to-energy systems is logistics. Even if ample feedstocks are available, demonstrated to be stable over time, and the core conversion technologies appear to be viable, significant resources will still be required to collect, characterize, monitor, handle, and transport both the influent and product materials. Additionally, one cannot underestimate the importance of the seamless flow of *information* in coordinating all these diverse operations and maintaining communications among the primary actors and stakeholders: waste generators, transporters/haulers, and waste-to-energy system operators, as well as local community leaders and policy makers (Armington et al., 2018). Regular dialogue among stakeholders enhances overall system efficiency and resilience and can lead to evolution of the portfolio of technologies being utilized over time.

4. Conclusions and future work

Food waste is a major global problem requiring immediate action to mitigate negative impacts on the environment. The food processing industry generates significant amounts of waste, but relative to other stages of the industrial food system produces by-product material that is more homogeneous and contaminant free and produced at high per-site rates. Many food processing operations have already established methods of using wastes as feedstock for value-added products such as nutraceuticals and other secondary food items, but there are opportunities for producing biofuels as another valorization strategy in cases where conventional disposal methods of landfilling, wastewater treatment, and incineration are currently being used.

AD, fermentation, TC, and transesterification can be used to produce a wide array of useful biofuels, including methane, hydrogen, ethanol, butanol, and biodiesel. The most economically favorable option depends upon many factors, with the specific phase of the waste material being perhaps the most important consideration. Whereas low moisture content solid wastes may be suitable for gasification or pyrolysis, liquid-phase wastes high in lipid and/or carbohydrate content are probably best suited for AD. A smaller subset of feedstocks appears to have viability for production of liquid fuels (ethanol and butanol) via fermentation processes. All of the technologies described in this chapter have been demonstrated at laboratory scale, and in most cases, the fundamental science is fairly well established. The challenge going forward is in applying sound engineering and design practices to minimize capital investment and operating costs and enhance adaptability to enable conversion systems to accept the widest possible array of diverse feedstocks. Because food waste resources are known to have significant spatial, temporal, and compositional variability, it is desirable for processes to be flexible enough to accept food and other more stable nonfood resources, such as municipal wastewater and biosolids, animal manure, and forest and lawn residue.

Although much of the research and development activities in food waste-to-energy processes have focused on large volumes of waste streams typically encountered in developed countries, there are many opportunities for utilizing available waste feedstocks in the rapidly expanding economies of Asia and Africa. For example, West Africa produces many commodity foodstuffs distributed worldwide and thus has massive resources of food processing wastes available for conversion to value-added products, including biofuels (Duku et al., 2011; Thomsen et al., 2014). A particularly compelling opportunity relates to cocoa bean production, amounting to a total of 4.7 million tons in 2016—17, where 75% of the whole fruit mass is the excess cocoa pod husk that is usually discarded (Lu et al., 2018).

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