Developing efficient and cost-effective use of wastes as feedstocks

The Gap

Sewage sludge and municipal solid waste are large streams of potential alternative fuel feedstocks that are currently underutilized due to the technical challenges of mixtures that are low-density and/or heterogeneous. Addressing these technical gaps would provide the opportunity for dramatically lowered biofuel costs (due to low or negative-cost feedstocks) with minimal land use change and other impacts and the added benefit of reducing landfilling volumes and/or water treatment costs.

Background

Municipal and industrial waste streams are something that society currently pays to treat and discard. Some 8.2 million tons of sewage sludge from wastewater plants and 250 million tons of municipal solid waste (MSW) are produced annually by the United States (U.S. EPA 2012). The nation's water systems spend about $4 billion per year to treat wastewater, or up to one-third of a municipality's total energy bill, (Star 2012) whereas municipalities pay roughly $22-40/ton (total of $5.5-10b annually) to dispose of MSW. Tipping fees in Europe and Japan are above $100/ton, with costs projected toward $200/ton by 2015.

Both liquid (sewage/wastewater) and municipal solid waste (MSW) thus represent a large and continuous source of potential feedstocks that would be free or potentially negative-cost to acquire. However, there are several key barriers to the use of these abundant feedstocks that have hindered extensive deployment, namely:

- Separation methodologies/costs to concentrate substrate of interest
    - Dewatering of sewage sludge
    - Separation of MSW fractions, e.g., for cellulosic material
- Methodologies to facilitate accessibility of substrate for intended processes
    - Improved lipid solubility (sewage)
    - Improved cellulosic material pretreatment (MSW, particularly for fermentation)
- Improved microbial processing
    - Selection of organisms that can tolerate conditions associated with wastes, e.g., pharmaceutical chemicals in sewage
    - Selection of organisms for maximum lipid production

Separation challenges

The best approach for sewage sludge requires removal of lipids already present in the sludge (15% dry weight) followed by treatment with microorganisms that can convert some of the remaining material into lipids (up to 7% yield). Separating lipids from the sludge at both stages is challenging due to the large volume of liquid (about 99%), the adsorption of lipids onto sludge solids, and the fact that optimal temperature and other lipid extraction parameters are different for the primary and secondary sludge fractions.

For municipal solid wastes, the material is not liquefied and is highly heterogeneous. This may be acceptable for thermocatalytic conversion technologies such as Fischer-Tropsch, which is capital intensive and not suitable for all locations, as well as for pyrolysis, a less costly emerging pathway. , However pre-sorting of carbon-rich materials (biologics, plastics, tyres etc) from metalic and inorganic wastes are likely to be required (Rapier 2012) Yet, separation into organic versus inorganic fractions remains important for fermentation and digestion processes. The biomaterials found in MSW typically have higher amounts of cellulose and hemicellulose than crops such as corn and sugar, and their efficient, cost-effective depolymerization remains a key challenge for processes such as fermentation (which can lead to the alcohol-to-jet pathway). (Ragauskas et al. 2006) High-capacity facilities that are capable of processing a mixed-MSW stream to extract a refined organic feedstock are then required.

Substrate Accessibility

A feedstock substrate of interest must be made accessible for the intended catalytic or other processes. This includes improving the solubility of lipids in sewage sludge and regulating the carbon/nitrogen ratio for increased microbial lipid production. Lipid solubility in the sludge reaction mixture is achieved by the addition of organic solvents such as hexane, then recovering the oil by distillation of the resulting miscella. Although the hexane can be reused, its use significantly increases the fuel production cost. For MSW, improved cellulosic material breakdown is required if using fermentative processes (this step is not necessary if using pyrolysis or Fischer-Tropsch). Cellulosic breakdown for ethanol has been the subject of intensive research over the last decade, but to date there are no functioning commercial facilities. Pretreatment options for research include acid hydrolysis or stable, low-cost enzymes for cellulosic material breakdown into component sugars for organisms to access and ferment. (Lynd 1996) This would enable the use of cellulosic materials (including MSW) for alcohol-to-jet pathways or advanced fermentation pathways by companies that require a sugar feedstock for their GE microorganisms that produce drop-in fuels. (Scientific American 2012)

Microbial processing

A wide variety of oleaginous bacteria and yeasts have been reported (Stephanopoulos 2007, Subramaniam et al. 2010), yet few species have been studied on the actual substrate in an industrial setting. A major challenge in boosting biofuel production from sewage sludge is for wastewater operators to maintain an optimal oleaginous (oil producing) flora whose enzymatic action can keep up with the input of feedstock and also convert (or at least resist) the increasing concentrations of pharmaceutical chemicals present in municipal sewage. In the best case, well-adapted oleaginous (oil-producing) microorganisms are used for continuous conversion of pre-treated sewage substrate into secondary lipid yields.

Current Status

Both sewage dewatering and the separation of raw MSW have remained energy- and cost-intensive processes. Currently, about half of the cost of producing a biofuel from sewage sludge is due to centrifuge/filtering and drying processes. (Dufreche et al. 2007). For MSW, the separation of organic wastes also represents about half of the entire system cost. (Chester and Martin 2009)

At present, municipal wastes are not utilized extensively for biofuels, and instead electricity and heat are the primary forms of recovered energy, including via solid waste combustion and the use of landfill gas. However, in spite of the challenges outlined above, the industry outlook for the use of wastes in fuel production is quite positive. A number of companies have indicated plans to use MSW to make jet fuel, mainly through Fischer-Tropsch gasification of waste materials (e.g., Solena, Enerkem). Both companies have plans to produce large-scale commercial facilities in the next few years. (Fielding 2012) Fischer-Tropsch gasification avoids the need for pretreatment of cellulosic material but is capital intensive and is likely to be only one of a suite of processing solutions for MSW as a feedstock. A few companies have also indicated plans to produce ethanol (e.g., Qteros/Applied Cleantech partnership) or drop-in fuels (e.g., Terrabon) from sewage. No facilities are currently in commercial production, however, Solena has signed agreements with several airlines to provide 16 million gallons annually of neat alternative jet fuel starting in 2015. (Air Transport Association of America 2011) How the challenges outlined above will be overcome remains to be seen.

Approaches/Needed Research

Additional research is needed to address the barriers to unlocking the maximum potential of waste feedstocks for sustainable aviation fuel production. Already, a number of promising approaches are beginning to emerge and deserve immediate study.

For sewage, the mechanical dewatering at the front end remains cost-intensive, but there is opportunity to address this challenge in multiple ways. Filtering, centrifuge, and shear technologies need to be improved, or chemical processes to induce flocculation and separation of the solid phase may be developed. Depending on plant location, thermal drying can also be made more cost-effective through improved design of a solar drying system. However, eliminating the need to dewater the sludge altogether would represent an even greater advance, and there are promising directions that merit further research, including super critical water oxidation, near-critical water, and gas-expanded liquids. (Svanstrom et al. 2005, Ragauskas et al. 2006)

The parallel challenge for MSW, separation of the organic fraction from the waste stream, involves half of the cost of MSW-to-biofuel production. There are two paths to addressing this barrier: (1) technology improvements to improve separation efficiency and cost, or (2) eliminating the need for front-end separation by treatment of the raw MSW feedstock. The latter approach has been demonstrated at the single-ton scale through autoclaving, in which unsorted MSW is steam- processed at elevated pressure and temperature, isolating the cellulosic fraction. The cost of autoclaving is currently estimated as comparable to landfilling, but more improvements are needed to enable a commercial facility. (Holtman et al. 2010) Cost-effective separation of the cellulosic fraction of MSW would enable its use for alcohol-to-jet pathways or advanced fermentation pathways by companies that require a sugar feedstock for their GE microorganisms that produce drop-in fuels

Later in the processing of sewage, improved methods are needed to economically regulate the C/N ratio, a crucial parameter for the accumulation of lipids by microorganisms. Instead of supplementing the mixture with carbon sources (e.g., biomass hydrolysates), nitrogen could potentially be removed through new chemical or biological measures. (Schneider et al. 2012) In addition, new approaches to more cost-effectively increase lipid solubility in sludge need to be studied in depth. These include chemical hydrolysis, thermal treatment, and ultrasonic pre-treatment of sludge to improve lipid accumulation by microorganisms. The feasibility and constraints of scaling these up to plant scale, particularly sonication, should be investigated.

In terms of the microbial processing of waste feedstock, there is a vast parameter space for selecting and engineering oleaginous bacterial and yeast strains, enzymes, and biofilms that are simultaneously tailored to sewage and that produce more lipids. This presents the opportunity to also select for microbial conversion of feedstock into higher-value byproducts, such as carotenoids or fragrances, increasing the value of the waste stream conversion to make it economically viable sooner. (Ragauskas et al. 2006) Combinatorial searches should be conducted to identify and design these microbial strains and enzymes, simulating industrial growth conditions as opposed to the growth media typically used in laboratories. (Stephanopoulos 2007)

Benefits

Conversion facilities stand to reap multiple benefits if they can take advantage of waste-based feedstocks. In contrast to the high cost and seasonal-weather variability of producing dedicated agricultural feedstocks for fuel, sewage and MSW streams already exist and are reliable, increasing in volume, and currently available at no cost (Kargbo 2010). Landfill tipping fees are expected to continue to increase, while incinerators are expected to face mounting environmental pressure to close or upgrade pollution controls. The production of biofuels from waste produces new value to offset and profit beyond the costs of water treatment, landfilling, incineration, and other alternative waste fates. On the other hand, it should also be noted that once wastes become valuable raw materials for producing fuels, their costs may rise.

The use of waste streams as feedstock for biofuel production also provides multiple benefits to society. Substitution of agricultural crop-based biofuel, which can compete with food crops, means that food prices remain unaffected. Large land areas do need to be converted to grow biofuel crops, so unsustainable land use change is not involved. Waste-derived biofuels reduce ratepayer costs for waste landfilling and incineration as well as wastewater treatment, while at the same time providing water treatment that can improve surface water quality and solid waste detoxification in the process of production. Both the diversion of waste streams and the ultimate combustion of the biofuel in vehicles instead of petroleum lowers greenhouse gas and other emissions. Finally, the displacement of petroleum-based fuels promotes national energy independence goals.

One potential scenario is integrating the cellulosic fraction of MSW and the secondary sludge generated at wastewater treatment facilities. For example, growing the mixed consortium of microorganisms present in wastewater treatment operations under high C:N ratios results in a more specialized microbial community capable of accumulating oils similar to vegetable oils or animal fats (Mondala et al. 2012). These oils could be used to produce jet fuel. In this case, the feedstock for jet fuel production would originate from two wastes, secondary sludge and MSW, which would maximize the income streams for the biofuel production system.

A similar application could be implemented to treat industrial wastewaters using microbial seeds from wastewater treatment facility operations. The result would be a new biofuel production process that reduces the cost of treating specific industrial wastewaters, add value to secondary sludge (lipid production seed), and uses MSW as a carbon source, thus reducing the carbon load in landfills.

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