Using waste biomass for the sustainable production of industrial chemicals

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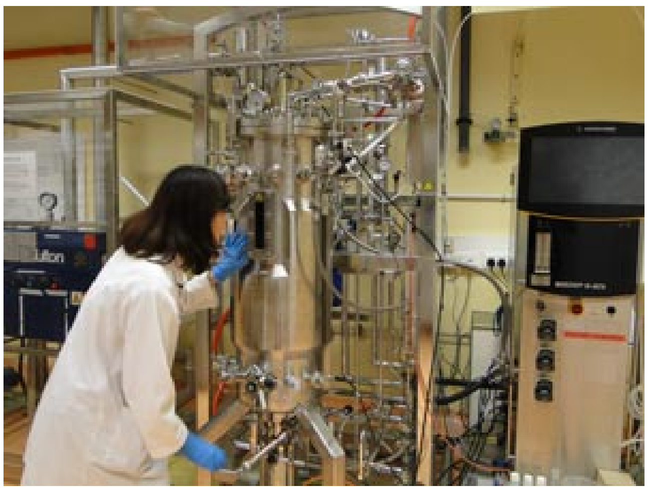

Bench-scale fermenters for biomass conversion experiments at ICES. Credit: A*STAR Institute of Chemical and Engineering Sciences

Each year more than half a billion tons of oil—more than an eighth of the total global oil consumption—are used to produce chemicals and plastics. The demand for oil leaves the petrochemical industry, with a market value slated to exceed US$758 Billion by 2022, critically exposed to oil price fluctuations and the uncertainty of dependence on a finite fossil resource. Researchers and chemical engineers around the world have been trying to find ways to use alternative raw materials such as agricultural waste or 'biomass' to replace petroleum in the production of common industrial chemicals as a step toward a more sustainable chemical industry.

In 2012, A*STAR brought together scientists working on research related to biomass feedstocks to form the Biomass-To-Chemical (B2C) programme. Led by the A*STAR Institute of Chemical and Engineering Sciences (ICES) in close collaboration with the Institute of Bioengineering and Nanotechnology (IBN), the B2C programme has worked towards developing a complete value chain, from raw biomass to commodity and specialty chemicals, as a commercially viable demonstration of biomass-based sustainable chemical production.

A local resource for global chemical production

Almost half of the world's petrochemical production occurs in Asia, which happens to have a rich source of waste biomass—the waste 'fruit' left over from palm oil production. Research at the ICES has focused on utilizing this cheap and local 'empty fruit bunch' (EFB) resource for sustainable chemical production.

"The biggest challenge we face is in cost-effectively converting EFB into the pure 'feedstocks' or basic chemicals needed for industrial chemical production," explains Wu Jinchuan, head of industrial biotechnology at the ICES. "For this we need to develop cheaper ways to obtain fermentable sugars from the biomass, and more powerful microbes for fermentation of the sugars to obtain useful feedstocks such as lactic acid in industrial yields."

Lactic acid is a food preservative and curing and flavoring agent, but is also used as a crude feedstock for the production of many other industrial chemicals. As a vital first link in the biomass-to-chemical value chain, Wu's team has developed a process for efficiently converting EFB to high-yield lactic acid by enzyme-driven hydrolysis followed by fermentation using thermophilic bacteria that occur naturally in Singapore as a vital first link in the biomass-to-chemical value chain.

"With this process we have shown that we can produce high-yield lactic acid from EFB," says Wu. "Our next step is to lower the processing cost further by refining the pretreatment and fermentation technologies."

From crude feedstock to industrial chemicals

Many industrial chemicals still rely on petroleum-based feedstocks, and finding a way to substitute a renewable feedstock like biomass-derived lactic acid in the production of a wide range of chemicals will be critical to driving a sustainable revolution in global chemical production.

The ICES Heterogeneous Catalysis division, under the leadership of Armando Borgna, is working on the conversion of lactic acid to common industrial chemicals like acrylic acid, which is normally produced from petroleum-based propylene.

A 50 liter fermenter for biomass conversion at the ICES laboratory. Credit: A*STAR Institute of Chemical and Engineering Sciences

"Acrylic acid is an important commodity chemical used for superabsorbent polymers, plastics, and synthetic rubber, as well as in the manufacture of coatings, paint formulations and leather finishing," says Choi Won Jae, head of the Bioprocess Engineering Centre and the B2C Programme Director. "There are intensive efforts going on worldwide to develop a biological-based method to produce it from a renewable feedstock. Our approach using lactic acid allows us to make use of EFB, which is a non-food resource that is cheap and readily available as a waste derived from the world's largest palm oil mills here in southeast Asia."

The critical part of the lactic acid to acrylic acid conversion process is finding an efficient way to catalyze the dehydration of lactic acid. Choi and his team have been studying the use of multi-element inorganic materials as a catalyst for this reaction, but the key challenge has been the low yield of acrylic acid from this process due to unwanted side reactions. Recent breakthroughs, however, have shown significant promise.

"Through structural engineering and advanced surface modification of the catalyst material, we have been able to increase the yield of acrylic acid to more than 80 per cent, which is by far the best performance ever reported for this reaction," say Choi.

To support the B2C programme, the ICES has brought all of these technologies together to establish an integrated biorefinery process specifically for the production of acrylic acid from EFB. The process encompasses the entire value chain with research teams working on each operational unit, from biomass pretreatment, enzymatic hydrolysis and fermentation, to separation, purification and catalytic conversion of lactic acid to acrylic acid.

"At the ICES we have world-class facilities, excellent scientists from all over the world, and strong financial support from the Singaporean government," says Wu. "We have all the facilities needed for our research—Parr reactors for pretreatment of biomass to extract fermentable sugars, fermenters to convert sugars to various chemicals by microbial fermentation, and a range of supporting facilities such as automated liquid handling systems, robotic colony pickers, and a plasma generator for isolating microbes and genetically modifying them to improve their performance for chemical production."

Exploring chemical diversity

At the Institute of Bioengineering and Nanotechnology, scientists involved in the biomass-to-chemical research coordinate with their colleagues at ICES through the Bio-Renewable Chemicals from Biomass programme led by Yugen Zhang.

"Here we are working on the conversion of biomass resources to a wider range of industrial chemicals," says Zhang. "Chemicals such as adipic acid, maleic anhydride, acrylic acid, butadiene and furandicarboxylic acid, are very important for the polymer industry. Our scientists are doing cutting-edge research that capitalizes on our expertise in many different fields, including catalysis, organic chemistry and materials."

Under the IBN programme, researchers have developed highly efficient processes for a number of industrially important reactions, including the conversion of mucic acid to adipic acid—a fundamental step in the production of nylon—and of sugars to furandicarboxylic acid, which is an important emerging bioprocess with many potential applications in polymer production and medicine.

"In our research we focus on increasing the selectivity of the reactions, which increases yield and lowers the cost of the overall process, which is the major challenge for the use of biomass in chemical production," says Zhang.

Despite the obstacles, the potential of industrial biomass-to-chemical production make it very much worth the effort and investment. "This research field is very exciting," says Wu. "Converting renewable resources to value-added chemicals is sustainable in a way that fossil fuels will never be. Even when the price of petroleum is low, biomass conversion is still commercially promising, particularly for specialty chemicals."

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