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BIOTECHNOLOGY FOR A RENEWABLE RESOURCES CHEMICALS & FUELS INDUSTRY: BIOCHEMICAL ENGINEERING R&D

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ABSTRACT

To establish an effective biotechnology of biomass processing for the production of fuels and chemicals, an integration of research in biochemical engineering, microbial genetics, and biochemistry is required. Reduction of the costs of producing chemicals and fuels from renewable resources will hinge on extensive research in biochemical engineering.

TECHNOLOGY SUBSTITUTION

Capital, the basis for new industrial investment, is generated from a surplus of production, the extend of which depends strongly on the cost of available energy and materials. The major sources of energy and materials used at present for industrial production are nonrenewable. In general, the more easily available resources are mined first. As they become less accessible and if technological advances in mining are not dramatic, prices must increase, especially since energy-and materials-yielding operations are capital-intensive.

Fortunately, an ongoing search for substitute materials is essential to the chemicals industry. The trend toward exhaustion of resources is bound to be offset by substitution of renewable resources [1]. The last barrel of oil, tonne of coal, or kilogram of uranium is unlikely ever to see the light of day. The high cost of nonrenewable resources will dictate a move toward renewable resources a long time before nonrenewable resources are exhausted.

Motivation for substituting biomass-derived chemicals for certain key petrochemicals is likely to grow. Ethylene, for example, is the leading petrochemical in regard to volume for production, sales value and number of derivatives. In the United States and Europe, the demand for ethylene is more than 10 million tonnes per year [2]. The price of ethylene is hovering near 44¢/kg. Its cost of production is bound to rise because booming shortages in natural gas will force a greater use of naphtha or gas oil instead of light feedstocks such as ethane or propane. The amount of naphtha used per tonne of each product in the manufacture of polyvinyl chloride resins, polyesters, and nylon fibers is about 2, 3, and 5 tonnes, respectively. The economic stage is set for fermentation products to begin displacing petrochemicals as prime chemical feedstocks. For example, ethanol can be converted quite readily and efficiently to ethylene using catalytic processes.

Substitutions such as these do not, of course, occur simply according to market forces of supply and demand; they evolve in association with a complicated sociopolitical milieu. For example, the impact of large chemical and petroleum companies operating internationally and interacting with various governments and legal systems is not inconsequential. A successful industrial substitution generally is a gradual, rather than sharp, transition.

DORMANT FERMENTATION TECHNOLOGY CAN BE REVIVED

Fermentation technology is of ancient origin. Before 1860, it was practiced successfully for thousands of years without any understanding that microorganisms were the causative agents. Following Louis Pasteur's discoveries and convincing demonstrations of fermentation and putrefaction, the technology slowly began to develop. Only after 1940 was there a pronounced rate of growth, partly owing to the discovery of penicillin. Also, chemical engineering advances in the previous decade were exploited: mixing and aerating techniques and progress in large-scale sterilization.

The fermentative production of bulk chemicals, particularly for use as solvents, became a robust industry. Ethanol, n-butanol, acetone, and lactic acid were produced commercially on a large scale. But from 1950 onwards, competition from the very effective technology of catalytic cracking of cheap petroleum began to hurt the fermentation industry. The economic challenge could not be met, and much of the industry went into abeyance.

Fortunately, however, the pharmaceuticals industry thrived, partly resulting from its incorporation of the results of research in molecular biology. The process engineering technology itself, however, remained conventional. Of approximately 5×10^9 kg of chemicals (butadiene, butanol, acetone, isopropanol, ethanol, methyl ethyl ketone, glycerol, fumarate, and maleic anhydride) produced annually in the United States, less than 10% of these are manufactured fermentatively. For ethanol there is an encouraging trend: from 1974 to 1976, the quantity of industrial alcohol produced by fermentation increased from 10% to 30% [3].

A first step in substituting biomass chemicals for nonrenewable sources is likely to be the use and modification of existing fermentation plants. Many of these, having gone out of business, have been dormant. Fifty breweries in the United States are idle [4]. During the heyday of acetone-butanol fermentation in the 1940s, fermenters, each with a capacity of half a million gallons, were constructed. Many of these fermenters are now idle and could be reinstated for fermentation processing.

NEED FOR BIOTECHNOLOGY RESEARCH AND DEVELOPMENT

If biomass chemicals are to penetrate the market effectively, there is a need for research and development. In a published overview of the biotechnology required for biomass processing, two goals for research and development are recommended [5]:

- A near-term objective to revive the older fermentation technology based on readily fermentable substrates and to reduce the cost of production to a competitive level; and
- The long-term development of a new biotechnology for producing chemicals and fuels efficiently from biomass of various kinds.

The near-term revival and improvement of the conventional fermentation industry for the production of bulk chemicals will require active research work in chemical and biochemical engineering as well as in microbiology and genetics. This article emphasizes the potential of chemical and biochemical engineering research. Because it can be used as human food or animal feed, the fermentable substrate is expensive. It constitutes about 65% to 70% of the cost of production. Less can be done about reduction of substrate cost than about processing cost.

The low energy efficiency of fermenter product recovery is a key problem. For example, about 70% of steam costs in any anhydrous ethanol plant can be attributed to the distillation section [6]. The typical chemical engineering stagewise unit operation uses energy poorly; it functions far from equilibrium with large changes in entropy. Conventional unit operations may be improved, for example, by incorporating heat pumps and other conservative devices [7]. Also new separation processes such as membrane separation, adsorption, and crystallization need to be developed.

Bioreactor performances can be improved by using a continuous rather than a conventional batch-type operation. Process variables will require closer control, perhaps with the aid of on-line computer systems. Algorithms for optimal control strategy need to be formulated. New instrumentation must be devised. For example, the respiration rate of a culture in a fermenter is determined from the inlet and outlet gas composition, flowrates, and cell density. For a computer control decision, these parameters must be measured precisely [8].

To improve the productivity of a fermentation system, higher cell densities are necessary. Cell recycle systems are being developed; a four-fold improvement in ethanol productivity has been achieved [9].

Fermentation product toxicity is a limitation. Removal of ethanol by vacuum fermentation reduces effects of product inhibition and permits faster fermentations [10], although large amounts of carbon dioxide and water vapor must be withdrawn at the same time.

Successful designs of novel bioreactors are essential and are emerging steadily from Europe and Japan. The poor mixing characteristics and high power demand of classic stirred reactors have encouraged designs such as the Imperial Chemical Industries' pressure-cycle reactor, air-lift loop fermenters, deep-jet systems, and the Torus bioreactor of ETH, Zurich. In these bioreactors, design goals are firm control over the hydrodynamics of the system and low power consumption [11].

The immobilization of microbial cells in various matrices permits a higher flow rate through the bioreactor [12]. The efficiency of gel-entrapped yeast cells for ethanol production from glucose has been demonstrated [13]. The fermentation of cheese whey lactose could potentially yield 150 million gal. of ethanol per year in the United States. The feasibility of immobilizing cells of K. fragilis for this conversion has been shown [14]. Tower fermenter design with flocculent yeast has been applied in the brewing industry [15].

Microbiological research is needed to develop thermotolerant yeast and bacterial strains to permit fermentation at higher temperatures and reduce energy expenditure on cooling. Higher fermenter temperatures are advantageous for vacuum fermentation. Microbial strains tolerant of sugar and fermentation product need to be developed. Research work in genetics and biochemistry is required.

The task of bringing former fermentation operations to commercial readiness would be aided by knowledge of operating conditions recorded in plant logbooks. These could be reviewed and process modifications planned. Some of the existing plants could be used, with a suitable joint input of private and federal funds, as ready-made process demonstration units (PDU). From accounting archives, equipment and operating costs could be gleaned. Such information on costs, brought up to date, could be used for an economic evaluation of process engineering. There are few adequate recent studies of this kind for fermentation processes. Among specific processes that could well prove profitable for resuscitation are the acetonebutanol fermentation and lactate production.

Carbohydrates such as cellulose and hemicellulose, although not readily fermentable, are abundant. About 2×10^{11} tonnes per year of carbon with an energy content of 3×10^{21} J are fixed by photosynthesis, which is 10 times the actual energy used in the world [16]. Lignocellulose provides a basis for the extensive development of a new biotechnology for the production of chemicals and fuels. In the United States, for example, about 500 million acres are covered by commerical forest. Less than 15% of these acres is managed; there is scope for a considerable improvement in yields of biomass.

Two chief problems are associated with the hydrolysis of cellulose to produce sugars: (1) lignin shields this polymer; and (2) the crystallinity of cellulose makes it resistant to enzymic attack. The classic Schoeller-Madison dilute acid hydrolysis process for a semicontinuous process gives poor yields and low concentrations of sugars. The cost of the reactor is high. Improvements are being designed such as continuous, low-residence time operation [17] and the use of screw-conveyor hydrolyzer systems [18]. Various techniques for pretreatment of biomass before its biological conversion are being investigated [19,20].

Natick Laboratory is a pioneer in the enzymatic conversion of cellulose and has developed a fungal strain with cellulose-splitting activity. Wang's group at Massachusetts Institute of Technology is converting biomass directly, without pretreatment, by using anaerobic microbial strains to produce ethanol and other chemicals [21]. Humphrey's group at the University of Pennsylvania is developing a process for solubilizing lignin in butanol, followed by hydrolyzing cellulose and hemicellulose biologically [22].

The only biotechnological process, however, that has been operated successfully using a refractory feedstock, at greater than the bench scale, is the Emert process. Municipal solid waste is used as a feedstock. Cellulose is hydrolyzed enzymically, and the resulting sugars are immediately fermented by yeasts. From 1 tonne/day of waste comprising 55% cellulose, 75 gal./day of ethanol (190 proof) are produced [23].

Vegetative forage crops, which have a lower lignin content than woody biomass, for example, could be a potential source of chemicals [24]. The production cost of ethanol by this route is appreciable ($1.64 gal. using vegetative Sudan grass). Costs of feedstock could be reduced by developing the use of unconventional crops [25].

For efficient conversion of material in the solid phase, such as biomass, new biochemical engineering design techniques are required. The typical biomass reactor is essentially a packed-bed reactor system, but with a disappearing solid phase. Adequate quantitative information on rheological behavior, particularly with regard to time-dependent systems, is needed. The design of heat-transfer equipment for biomass processing will depend on suitable rheological information.

Apart from lignocellulose conversion, the production of hydrocarbons from microbial and plant sources offers undoubted potential. Tornabene [26] has investigated productivities of various algal, fungal, and bacterial species. A problem with some promising algal species is their low growth rate, a problem that might be alleviated by genetic technology and physiological manipulation. Euphorbia, an oil-producing plant, was cultivated in Morocco, before World War II by the French; yields of 3 tonnes/hectare were obtained [27].

A strategy for reserch and development in biotechnology has been designed at the Solar Energy Research Institute [5]. Here biotechnology is an integrated set of disciplines comprising biochemical engineering, microbial genetics, and biochemistry. A particular emphasis is the exploitation of modern genetic technology [28]. From basic and applied research by the science groups, data are generated. This information is transferred to the engineering group, where it is used for process design and scale-up. A prime function of the biochemical engineering group is discriminatory: from process engineering evaluation and steady-state optimization, potentially commercial areas of research and development can be identified.

Integrated work in genetic technology, biochemistry, physiology, and biochemical engineering can advance the development of a chemicals/fuels industry based on renewable resources.

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