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Introduction

In the United States, billions of pounds of cheese whey permeate and approximately 10 billion pounds of potatoes processed each year are typically discarded or sold as cattle feed at $3-6/ton; moreover, the transportation required for these means of disposal can be expensive. As a potential solution to this economic and environmental problem, Argonne National Laboratory is developing technology that

- Biologically converts existing food-processing waste streams into lactic acid and
- Uses lactic acid for making environmentally safe, degradable polylactic acid (PLA) and modified PLA plastics and coatings.

An Argonne process for biologically converting high-carbohydrate food waste will not only help to solve a waste problem for the food industry, but will also save energy and be economically attractive. Although the initial substrate for Argonne's process development is potato by-product, the process can be adapted to convert other food wastes, as well as corn starch, to lactic acid. Proprietary technology for biologically converting greater than 90% of the starch in potato wastes to glucose has been developed. Glucose and other products of starch hydrolysis are subsequently fermented by bacteria that produce lactic acid. The lactic acid is recovered, concentrated, and further purified to a polymer-grade product.

PLA Market Potential

We believe that one promising end use for degradable PLA is in controlled-release coatings for fertilizers and pesticides. A collaborative study between Argonne and the Tennessee Valley Authority's National Fertilizer and Environmental Research Center is examining the efficacy of PLA for sustained release of urea-based fertilizers. Other potential markets for degradable polylactic acid plastics and coatings include the following:

- 150 million pounds for agricultural mulch films,
- Tens of millions of pounds for specialty bags/sacks (i.e., compost or yard-waste bags),
- 500 million pounds for marine plastic applications, and
- Greater than 200 million pounds for degradable conditioner coatings for paperboard stock.

PLA is a polyester that can be obtained by direct self-condensation of lactic acid. This method, however, does not produce PLA with a high enough molecular weight to be useful. Lactide polymerization is currently the only known means of obtaining high-molecular-weight PLA. Argonne is developing proprietary technology that can produce high-molecular-weight PLA by a more cost-effective route.

The objectives of current PLA research at Argonne also include development of PLAs that have custom-tailored properties for their intended applications. Each potential application of PLA requires some specialized properties. For controlled-release coatings for fertilizers and pesticides, for example, increased water sensitivity is desirable. If lactide is copolymerized with monomers that are more hydrophilic than lactic acid itself (e.g., ethylene oxide or glycolic acid), the susceptibility of PLA to hydrolytic degradation can be increased significantly. Argonne has also developed the first photodegradable PLA, a plastic susceptible to both ultraviolet (UV) scission and water hydrolysis.

Lactic Acid Fermentation and Purification

Overview of the Process

The process shown in Figure 1 has been conceptually designed to allow for cost-effective production of polymer-grade lactic acid from inexpensive carbon sources, such as potato waste. The process mainly consists of a continuous fermenter, an electrodialysis system, and some polishing and concentrating steps. The continuous fermenter is a cell-recycle-type fermenter. A membrane filter is used to maintain a high cell concentration in the fermenter, while the cell-free fermentation broth can be continuously withdrawn. In the fermenter, glucose is converted into lactic acid, which in turn is instantaneously neutralized by sodium hydroxide to sodium lactate to maintain the fermentation pH. In the electrodialysis process, the sodium lactate is converted into lactic acid and sodium hydroxide. The lactic acid stream udergoes additional polishing and is concentrated to produce the polymer-grade lactic acid.

The Argonne process is conceptually designed using the systems approach to achieve cost-effectiveness and to minimize waste generation from the process. For example, in the primary product-recovery step, electrodialysis, the recovery of sodium hydroxide not only reduces a waste disposal problem but also represents a significant saving of chemical and related costs. The advent of bipolar membranes has significantly improved the feasibility and economics of this processing technology. Additional technical considerations relevant to the lactic acid process are discussed below.

Product Stereospecificity

Lactic acid exists as two optical isomers (D- and L-lactic acid). Lactic acid bacteria can produce D-, L-, or DL-lactic acid. The desired product stereospecificity is influenced by the intended applications of lactic acid. It is expected that the synthesis of degradable PLA will be the most significant market growth for lactic acid. For such applications, it is desirable to have both L-specific and racemic (D/L = 50/50) strains available.

Continuous Fermentation

In general, industrial applications of continuous fermentation are hampered by the frequency of microbial contamination and the difficulty in maintaining an appropriate cultural physiological state for the desirable product. For lactic acid fermentation, these are not serious concerns. Our continuous runs demonstrated that contamination was not a problem; the longest run extended over more than three weeks. The steady-state performance, a productivity of 5.7 g/(L·h) at 90 g/L lactic acid and 0.03 g/L glucose, compares well with data reported in the literature for continuous lactic acid fermentation using a glucose-based medium.

Purification

Lactic acid to be used for polymer synthesis requires high purity. Of particular concern is the presence of residual sugars. Inexpensive carbon sources normally contain variable levels of impurity sugars (e.g., fructose, maltose, and higher oligosaccharides) in addition to the primary sugar component (e.g., glucose). Although almost all of the primary sugar can be fermented, significant levels of the impurity sugars are usually not consumed. To characterize the level of residual sugar in the lactic acid produced, it is convenient to use the ratio of total reducing sugars (TRS) to lactic acid (LacH) as an index of product purity. For a lactic acid fermentation using hydrolyzed potato by-products or corn starch, the TRS/LacH value of the broth is typically 5-10% for batch fermentation and 2-7% for continuous fermentation. Continuous fermentation appears to result in a somewhat higher broth quality.

Promising methods of lactic acid purification (polishing) include esterification and liquid-liquid extraction. The esterification method, which involves esterification, hydrolysis, and distillation, has high selectivity and has been demonstrated to generate a seemingly heat-stable lactic acid sample in our laboratory. Liquid-liquid extraction using the tertiary-amine-based system has also been proposed for lactic acid purification. However, its selectivity is somewhat lower, and phase separation and process synthesis tend to be difficult for extraction.

Conclusions

The market demand for PLA — and thus, for lactic acid — is expected to increase significantly in the near future. As lactic acid becomes a commodity product, the cost of the raw material (i.e., carbon source) will be increasingly important for the process economics. For this reason, lactic acid fermentation using inexpensive food-waste streams is attractive. Traditional concerns about utilization of food wastes include availability at the point source, stability of the material, and costs of transportation. Also, the technologies involved in the final purification of lactic acid seem to be more sophisticated than those at the front end of the process. Therefore, it seems desirable to carry out the front end of the process at or near the sources of waste streams. The intermediate product (e.g., a crude sodium lactate or lactic acid solution), which is more concentrated and stable, can then be transported to a central plant for further processing to yield the purified lactic acid. This approach would reduce the need for technical expertise at plant locations and would allow the central plant to achieve the economy of scale. This scenario should be particularly attractive for regions where concentrated potato processors or dairy farms exist.

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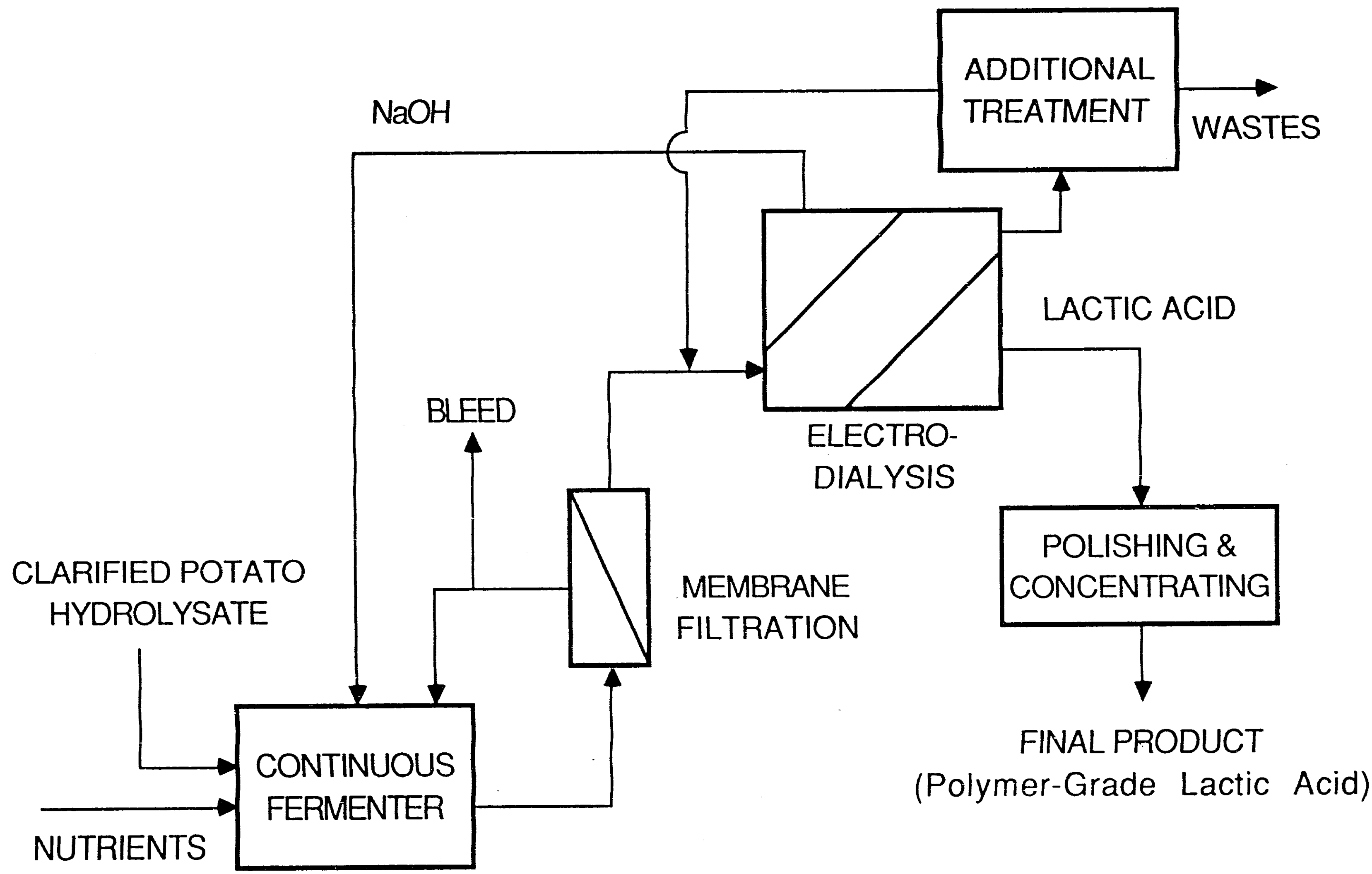

Figure 1. Flowchart of the Argonne Lactic Acid Process

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