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# Economic Analysis of Ethanol Production from Citrus Peel Waste

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**The Florida citrus juice industry produces about 3.5 million tons of wet peel waste per year. In current industrial practice, the peel waste is dried and sold as cattle feed to offset the waste disposal cost. Profitability would be greatly improved if the peel waste could be used to produce higher value products. Recent advances by USDA/ARS scientists and their partner Renewable Spirits, LLC have given rise to the potential of a new process for making fuel ethanol from citrus peel waste. In this paper, the economics of the process for making citrus ethanol are analyzed and discussed. The economic model for the cellulose-to-ethanol process was used as a benchmark to estimate the project cost and the fixed operating cost for the peel-to-ethanol process. The production cost of citrus ethanol is estimated to be approximately $1.23/gal, possibly higher than the cost of corn ethanol ($1.00/gal), but lower than the cost of cellulose ethanol ($1.35–1.62/gal). This study allows us to pinpoint the economics of the process for making fuel ethanol from citrus peel waste, and is useful for predicting the cost benefit of proposed research and its economic impact on the juice industry.**

The citrus industry plays an important role in Florida's economics. For the 2003–04 season, its total economic impact was estimated at $9.26 billion, $3.69 billion sales revenue, and 76,000 associated jobs (Hodges et al., 2006). The citrus juice industry produces 3.5~5.0 million tons of peel waste per year, which are currently dried and sold as low-value cattle feed to offset the waste disposal cost. In order to compete effectively in the global market, it is critical for the Florida citrus industry to make use of the enormous amount of peel waste to produce higher value products and co-products, such as ethanol, limonene, pectin, and/or pectin derivatives.

In particular, fuel ethanol from biomass is attractive for many reasons. First, ethanol is an alternative for methyl tertiary butyl ether (MTBE), a fuel additive that is now banned in many states for causing environmental pollution (Chisala et al., 2007). Although Florida has not yet banned the use of MTBE, it is believed that more and more states will impose similar mandates on fuels and promote the use of ethanol. Secondly, the use of fuel ethanol from biomass is sustainable and environmentally friendly. According to the life-cycle analysis of bio-ethanol conducted by the National Renewable Energy Laboratory (NREL), compared to gasoline, bio-ethanol reduces $CO_2$ emission by 80% (Anonymous, NREL Technical Report, 2002). Thirdly, the use of ethanol reduces the dependency on imported oil, and thus increases energy security. As a result, ethanol blends (E10) are now widely used in the United States, Canada, and Europe. Recently, the US Department of Energy (DOE) announced an investment of $385 million for six cellulose ethanol projects over the next 4 years, aiming to produce 130 million gal of ethanol from cellulosic biomass per year (Stevens, 2007).

Research was carried out on converting citrus peel into fuel ethanol in the 1990s (Grohmann et al., 1992, 1994, 1995, 1998), but industrial interest lagged because of a cheap and plentiful supply of petroleum fuel. Over the last several years, Widmer, Wilkins, and coworkers continued the original work (Wilkins et al., 2007), and successfully reduced the enzyme costs from approximately $10.00/gal to $0.80/gal of ethanol (unpublished results). Although the relatively high enzyme costs make citrus ethanol potentially unattractive from an economic point of view, the recent, rapid increase in petroleum prices has improved the relative economics of this product. Moreover, in the conversion of citrus peel into ethanol, limonene is removed and recovered as a co-product during the pretreatment of citrus peel, offsetting some of the production costs.

To date, citrus ethanol has advanced from bench to pilot plant scale (10,000-gal mash/batch fermentation). However, the development of an economically viable process could be a challenge. In particular, due to the presence of residual solids, the fermented citrus peel waste is very viscous. Technically, distillation of viscous materials is difficult and needs to be demonstrated. The economic impacts of this new technology also need to be addressed and found favorable, so that the citrus industry would be interested in endorsing and ultimately implementing it. Although the cellulose-to-ethanol process and the peel-to-ethanol process consist of similar unit operations, the economics of the former has been studied extensively (Aden et al., 2002; Wooley et al., 1999), whereas the economics of the latter has not been fully investigated. In this study, we adapted the well-established economic model for cellulosic ethanol, and modified it to estimate the production cost of citrus ethanol. It is important to predict the economic impact of this new technology on the citrus industry, and provide viable solutions to practical problems facing the citrus processing industry and the emerging bio-ethanol industry.

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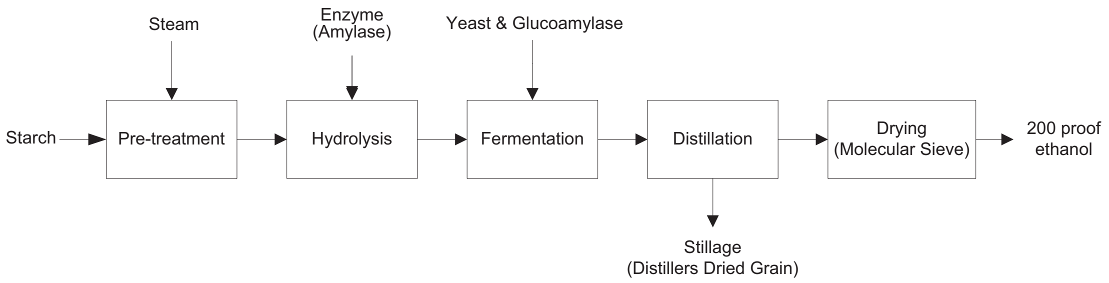
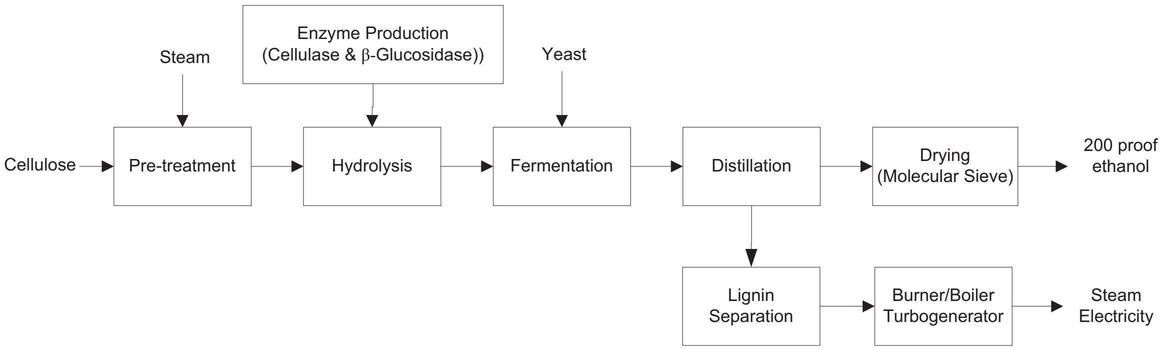
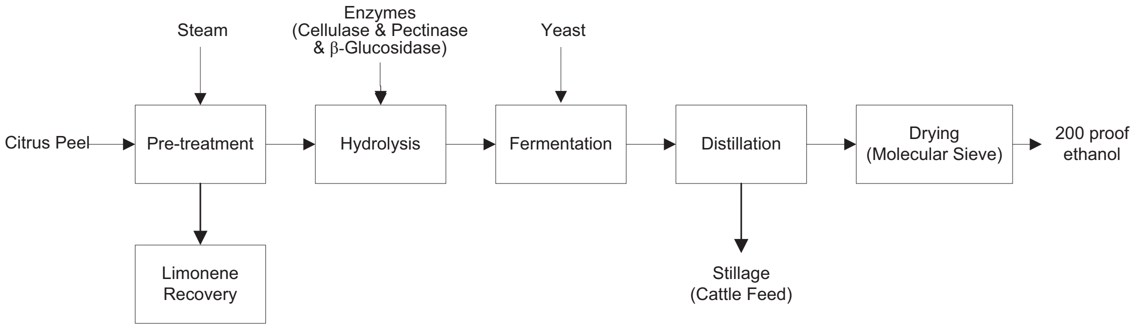


Starch-to-ethanol Process



Cellulose-to-ethanol Process



Peel-to-ethanol Process

Fig. 1. Process block diagram for making ethanol from different biomass resources.

## Process Description

**Processes for making ethanol from biomass.** The processes for making ethanol from different biomass sources using enzymatic hydrolysis are similar, with slight modification when different feedstocks are used. Figure 1 shows process block diagrams for making ethanol from starch, cellulose/hemicellulose, and citrus peel. Except for the co-product recovery and utilization, each process consists of similar unit operations, i.e., pretreatment, hydrolysis, fermentation, distillation, and drying.

In each process, the feedstock is first pretreated with steam and/or chemicals, and followed by the hydrolysis of polysaccharides (starch, cellulose, and hemicellulose) into sugar. Pretreatment not only sterilizes the feedstock, but also opens up the structures of cell wall polysaccharides, making them more accessible to enzymes (Chang et al., 1981; Fan et al., 1982; Grohmann et al., 1994). Subsequently or concurrently, the hydrolyzed sugars are fermented into ethanol by yeasts or bacteria. In the case of citrus peel, pretreatment also removes limonene, an inhibitor for the yeasts (Wilkins et al., 2007). Finally, the fermented mash is dis-

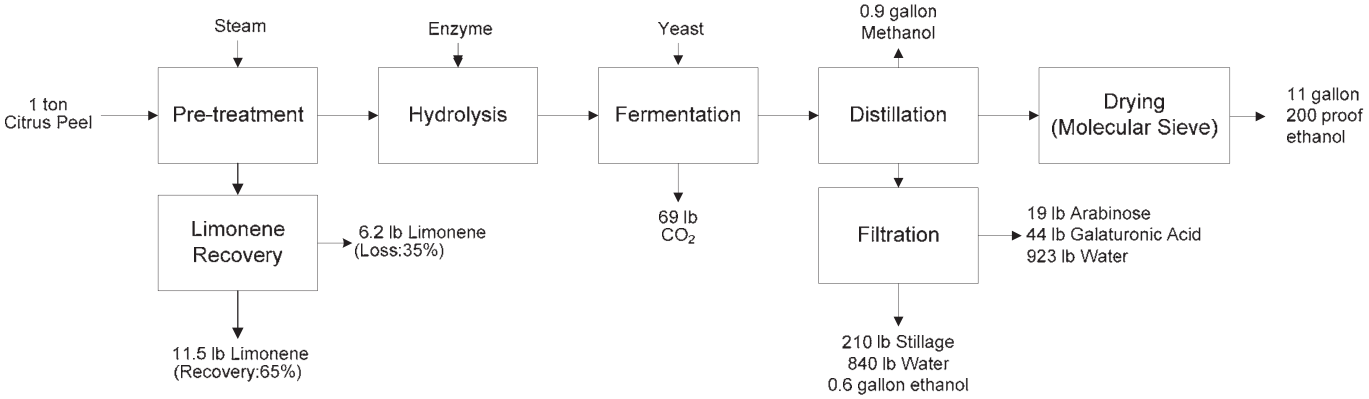


Fig. 2. Mass balance for peel-to-ethanol process (feedstock: citrus peel).

tilled, and the resulting concentrated ethanol is dried by molecular sieves to yield fuel ethanol.

Traditionally, there are four hydrolytic methods for converting biomass into ethanol. They are 1) concentrated acid hydrolysis, 2) dilute acid hydrolysis, 3) enzymatic saccharification followed by fermentation, and 4) simultaneous saccharification and fermentation (SSF). Mielenz compared these approaches and concluded that SSF is the least expensive (Mielenz, 1997). Besides, biomass can be gasified, and subsequently the resulting syngas (a mixture of carbon monoxide and hydrogen) can be converted into ethanol. Nevertheless, this method is not suitable for very wet biomass, such as citrus peel waste.

**Mass balance for peel-to-ethanol process.** Figure 2 shows the mass balance of the process for making ethanol from citrus peel by SSF. The mass balance is based on a pilot plant scale of 1 ton wet citrus peel per batch. Wet citrus peel consists of approximately 20% solids. The major components of the wet citrus peel are approximately 80% water, 6% soluble sugars, 5% cellulose and hemicellulose, 4% pectin, and 0.8% limonene (Grohmann, 1995). The density of wet citrus peel is 1030 $\mathrm{Kg\cdot m^{-3}}$ at 23 °C. After fermentation, the six carbon sugars (glucose and fructose) are completely converted into ethanol, and the resulting mash contains 4% to 5% ethanol by volume and less than 10% residual solids. After distillation, the residual solids can be dried and sold as cattle feed to offset the waste disposal cost or possibly converted into other by-products, but these alternative by-products have yet to be developed.

## Process Economics

The economic viability of bio-ethanol depends on four main factors: 1) cost of feedstocks, 2) values of product (ethanol) and co-products, 3) cost of processing, and 4) tax levels. The dominant cost could be different from process to process. It is concluded that for the cellulose-to-ethanol process, depreciation of capital is the dominant cost; and for the starch-to-ethanol process, feedstock is the dominant cost (McAloon et al., 2000).

**Production costs for citrus ethanol.** Production costs consist of variable and fixed operating costs. Variable operating costs include those of feedstock, chemicals and enzymes, waste disposal, and utilities (steam, water, and electricity), along with any co-product credits. Fixed operating costs include depreciation of capital, labor, supplies, and overhead expenses. The capital investment includes costs of equipment and installation.

**Basic assumptions and considerations.** Because the peel-to-ethanol process is similar to the cellulose-to-ethanol process (see Fig. 1), we adapted the economic model of the cellulose-to-ethanol process, developed by the scientists and engineers of NREL (Aden et al., 2002; Wooley et al., 1999) and USDA/ARS (McAloon et al., 2000), and modified it to estimate the production cost of citrus ethanol. It is assumed that for these two processes, the capital investments and the operating costs for pretreatment, hydrolysis, fermentation, distillation, and drying, are identical. In the cellulose-to-ethanol process, lignin is recovered and burned to generate steam and electricity, and thus the utility cost is not incurred for cellulose ethanol. Unlike most cellulosic biomass, citrus peel does not contain lignin, and thus the boiler/combustion unit is removed from the peel-to-ethanol process. Alternatively, we used the economic model of starch-to-ethanol process, developed by McAloon (McAloon et al., 2000), to estimate the utility cost for the peel-to-ethanol process. Typically, a fermented starch mash contains approximately 10% alcohol, and the energy consumption for distillation doubles if the alcohol content drops from 10% to 4.5% (Jacques et al., 2003). Since distillation accounts for most of the energy consumption in the production of ethanol, it is assumed that the energy consumption for the peel-to-ethanol process is twice as much as that for the starch-to-ethanol process. For the economic model of the peel-to-ethanol process, instead of integrating an enzyme production unit in the process, enzyme is purchased from a supplier to reduce the depreciation of capital investment. The depreciation rate is assumed to be 10%. For pretreatment, the limonene recovery is conservatively estimated to be 65% of that contained in the peel. For distillation, the ethanol recovery is assumed to be 95%. All the calculations were based on a production capacity of 25 million gal fuel ethanol per year in 2005.

## Results and Discussion

For the peel-to-ethanol process, Table 1 shows the production costs with and without the recovery of limonene. The pilot plant study conducted in our lab shows that in pretreatment, 1 ton of wet citrus peel yields approximately 11.5 lbs of limonene. The limonene content is reduced from 0.8 wt% to less than 0.1 wt% of the cooked peel. Our pilot results for fermentation have given ethanol yields of 71%, which is equivalent to a yield of 11 gal of ethanol per ton of wet citrus peel. However, in production facilities, ethanol yields typically run at 80% to 90% of theoretical yield. In other words, 12 to 14 gal of ethanol can be achieved in a properly run production facility.

Table 1. Production costs for the peel-to-ethanol processes with and without the recovery of limonene (capacity: 25 million gal/year; year for cost basis: 2005).

| | Limonene recovery | | No limonene recovery | |
|---|---|---|---|---|
| | Annual | Per gal | Annual | Per gal |
| Citrus peel[z] | $1,300,000 | $0.05 | $1,300,000 | $0.05 |
| Chemicals, waste disposal, and utilities | $35,000,000 | $1.40 | $30,700,000 | $1.23 |
| Labor, supplies, and overhead expenses | $5,200,000 | $0.21 | $5,200,000 | $0.21 |
| Depreciation of capital | $7,600,000 | $0.30 | $7,600,000 | $0.30 |
| Co-product credit (limonene) | –$18,300,000 | –$0.73 | $0 | $0.00 |
| Total production cost | $30,800,000 | $1.23 | $44,800,000 | $1.79 |

[z] Citrus peel price: $0.55/ton wet peel.

Ethanol yield: 11 gal ethanol/ton wet peel (recovery: 95%).

Limonene yield: 11.5 lb/ton wet peel (recovery: 65%).

Limonene price: $0.70/lb.

It is noted that of the variable operating costs, enzymes are the dominant cost, contributing $0.80/gal in the peel-to-ethanol process. For cellulosic ethanol, it is reported (Wooley et al., 1999) that on-site enzyme production could significantly reduce the enzyme cost by 50% (–$0.28/gal), but increase the fixed operating cost by $0.10/gal (the depreciation of capital would increase by $0.06/gal, and labor cost would increase by $0.04/gal). Accordingly, the net margin of a decrease for on-site enzyme production is estimated as $0.18/gal. Nevertheless, the enzyme prices are expected to decrease as the efficiency, productivity, and scale of enzyme production improve, whereas labor cost and capital investment are expected to increase. Therefore, for long-term commercial viability of the process, the net margin for on-site enzyme production may be insignificant.

Table 1 also shows that the recovery of limonene improves the economic viability of the process. The separation of limonene slightly increases the operating cost, but pays off $0.73/gal in co-product credit. This credit makes citrus ethanol more economically competitive than starch ethanol. More importantly, according to the Federal Clean Air Act Amendments (EPA, 1990), limonene is considered a volatile organic compound (VOC), and a Title V permit needs to be filed if the emission of limonene exceeds 100 tons per year (Odio, 1996; Wilkins et al., 2007). In the current industrial practice, significant amounts of limonene are emitted into the atmosphere while peels are being dried. Ethanol production from citrus peel requires the removal of limonene; otherwise the fermentation will not take place. This can be accomplished by steam stripping citrus peels and other methods. The stripped limonene can be easily separated and sold as a high value co-product. Therefore, ethanol production from citrus peel offers a solution for the citrus processors to reduce their VOC emission problems and help meet the federal mandates.

Table 2 shows the economics of citrus ethanol. For a 25 million gal/year citrus ethanol plant, the total capital investment is $76,000,000. The annual gross revenue is $63,200,000, of which limonene contributes approximately 30%. The net margin is estimated to be $14,100,000 /year. This indicates that the citrus ethanol project has a positive return.

Figure 3 compares the production costs for making ethanol from starch, cellulose, and citrus peel waste. The estimated production costs for starch ethanol, cellulose ethanol (corn stover), and citrus ethanol are $1.00/gal (corn price at $2.20/bu), $1.62/gal, and $1.23/gal, respectively. Figure 3 also shows that for starch ethanol, feedstock is the dominant cost, accounting for 77% of the production cost; for cellulose, ethanol, feedstock, and depreciation of capital equally contribute to 72% of the production cost; for citrus ethanol, enzymes are the dominant cost, accounting for 65% of the production cost.

This economic analysis shows that citrus ethanol has many advantages over starch and cellulose ethanol. First, compared to starch ($0.77/gal) and corn stover ($0.56/gal), citrus peel ($0.05/gal) is the least expensive feedstock for making ethanol. In order to minimize feedstock handling costs, ethanol processing facilities should be preferentially located next to or within 10 miles of citrus processing plants. For starch ethanol, as a result of several factors, the corn feedstock price has climbed from $2.20/bushel to $3.30/bushel or more over the past 2 years. Consequently, the production cost of starch ethanol has increased to $1.40/gal, approaching the production cost of cellulose ethanol. Secondly, maintenance and equipment costs would be less expensive for the pretreatment of citrus peel than for the pretreatment of other cellulosic materials. This is because citrus peel does not contain lignin, and thus acid or base catalyzed steam explosion is not required for the pretreatment of citrus peel. Thirdly, limonene has a higher value than distillers dried grain (DDG) and lignin. Limonene has been widely used as a solvent in a number of cleaning agents, such as degreasers, release agents, part washers, and dip baths. Currently, the price of limonene is $0.60 to 0.90/lb, and will increase if the use of halogen hydrocarbons is banned. For cellulosic ethanol, the value of its co-product (lignin) is relatively low. It should be noted that all the calculations were based on a production capacity of 25 million gal. Although the production cost of cellulosic ethanol could be reduced from $1.62/gal to $1.35/gal by doubling the production capacity (Eggeman et

Table 2. Citrus ethanol economics (capacity: 25 million gal/year; year for cost basis: 2005).

| Operating cost/margin | |
|---|---|
| 25,000,000 gal/year ethanol @ $1.80/gal | $45,000,000 |
| 26,000,000 lb/year limonene @ $0.70/lb | $18,200,000 |
| Gross revenue | $63,200,000 |
| Citrus peel | –$1,300,000 |
| Chemicals, waste disposal, and utilities | –$35,000,000 |
| Gross margin | $26,900,000 |
| Labor, supplies, and overhead expenses | –$5,200,000 |
| Depreciation of capital | –$7,600,000 |
| Net margin | $14,100,000 |

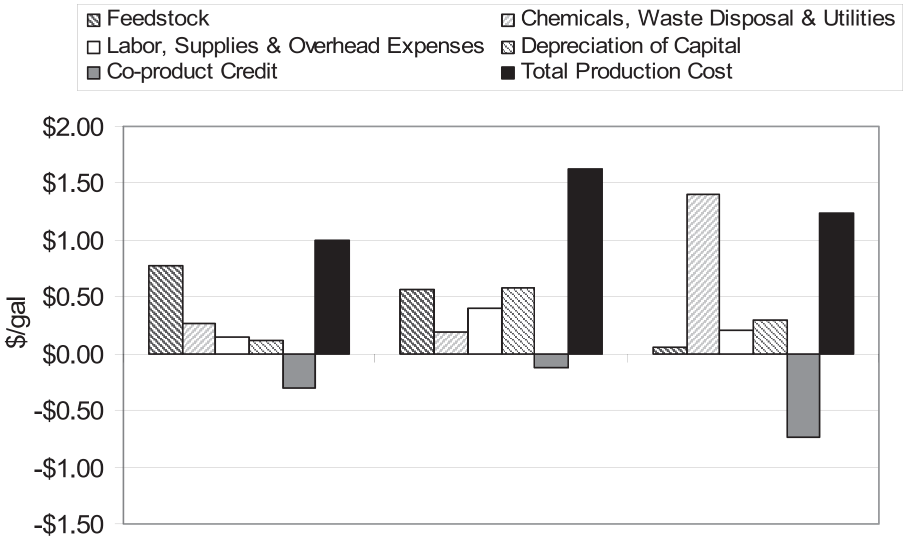


Fig. 3. Comparison of production costs for making ethanol from starch, cellulose, and citrus peel.

al., 2006), the economic viability of cellulosic ethanol is not as attractive at the present time as that of citrus ethanol.

This economic analysis also indicates that the economic viability of citrus ethanol has more potential to improve than that of cellulose ethanol in the bio-fuel industry. It should be noted that this economic analysis is based on the assumptions of a 65% recovery of limonene and a 95% recovery of ethanol. Both limonene and ethanol recoveries can be improved if the peel-to-ethanol process is well understood and properly designed. It was reported that over 90% recovery of limonene was achieved in Brazil (Odio, 1996). Besides, the economic analysis has not taken into account the recoveries of other potential valuable co-products, such as flavonoids, galacturonic acid, methanol, pectin, and pectin derivatives. Obviously, for long-term commercial viability, co-products could have a significant impact on the economics of the peel-to-ethanol process. Particularly, revenues would be greatly increased if applications of pectin residues can be identified and marketed.

This study shows that the production of ethanol from citrus peel is economically feasible. Practically, it is more feasible to build a 10 million gal/year ethanol plant in the vicinities of existing citrus processing plants, in which case the depreciation of capital per gallon of ethanol would be higher if the plant were scaled down in size. Although it would be more expensive to operate a smaller citrus ethanol plant, some of the existing equipment in citrus processing plants could be used for ethanol production, thus decreasing capital cost. It should be pointed out that in this analysis, we used a cellulose-to-ethanol economic model as a benchmark to estimate the operating costs. Consequently, all the cost estimates are subject to this model's accuracy. Since tax level and payout time also play an important role in the commercial production of citrus ethanol, cash flow analysis and sensitivity studies should be conducted before any commercial production of citrus ethanol takes place. This study also shows that ethanol production cost is sensitive to by-product credits and the development of value-added by-products can significantly improve the economics of fuel ethanol production from citrus waste.

## Literature Cited

Aden, A., M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, B. Wallace, L. Montague, A. Slayton, and J. Lukas. 2002. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis for corn stover. Natl. Renewable Energy Lab. Tech. Rpt., NREL/TP-510-32438. <http://www.nrel.gov/docs/fy02osti/32438.pdf>.

Anonymous, 2002. What is a life cycle assessment? Natl. Renewable Energy Lab. Tech. Rpt., NREL/PD-510-31792. <http://www.nrel.gov/docs/fy02/31792.pdf>.

Chang, M.M., T.Y.C. Chou, and G.T. Tsao, 1981. Structure, pretreatment and hydrolysis of cellulose. Adv. Biochem. Eng. 20:15–45.

Chisala, B.N., N.G. Tait, and D.N. Lerner. 2007. Evaluating the risks of methyl tertiary butyl ether (MTBE) pollution of urban groundwater. J. Contaminant Hydrology 91(1/2):128–145.

Eggeman, T. and R.T. Elander. 2005. Process and economic analysis of pretreatment technologies. Bioresource Technol. 96:2019–2025.

Environmental Protection Agency (EPA). The Clean Air Act Amendments of 1990. <http://www.epa.gov/air/oaq_caa.html/>.

Fan, L.T., Y.H. Lee, and M.M. Ghayusray. 1982. The nature of lignocellulosics and their pretreatments for enzymatic hydrolysis. Adv. Biochem. Eng. 23:157–187.

Grohmann, K. and E.A. Baldwin. 1992. Hydrolysis of orange peel with pectinase and cellulase enzymes. Biotechnol. Lett. 14(12):1169–1174.

Grohmann, K., E.A. Baldwin, B.S. Buslig, and L.O. Ingram. 1994. Fermentation of galacturonic acid and other sugars in orange peel hydrolysates by the ethanologenic strain of *Escherichia coli*. Bioresource Technol. 16(3):281–286.

Grohmann, K., R.G. Cameron,and B.S. Buslig. 1995. Fractionation and pretreatment of orange peel by dilute acid hydrolysis. Bioresource Technol. 54(2):129–141.

Grohmann, K., J.A. Manthey, R.G. Cameron, and B.S. Buslig. 1998. Fermentation of galacturonic acid and pectin-rich materials to ethanol by genetically modified strains of *Erwinia*. Biotechnol. Lett. 20(2):195–200.

Grohmann, K., E.A. Baldwin, and B.S. Buslig. 1994. Production of ethanol from enzymatically hydrolyzed orange peel by the yeast *Saccaromyces cerevisiae*. Appl. Biochem. Biotechnol. 45/46:315–327.

Hodges, A., M. Rahmani, and D. Mulkey. 2006. Economic impacts of the Florida citrus industry in 2003–04. EDIS document FE633, published Apr. 2006, Univ. of Florida, Inst. of Food and Agr. Sci., Food and Resource Econ. Dept., Gainesville. <http://edis.ifas.ufl.edu/pdffiles/FE/FE63300.pdf>.

Jacques, K.A., T.P. Lyons, and D.R. Kelsall. 2003. The alcohol textbook. 4th ed., p. 326. Nottingham Univ. Press, Nottingham, UK.

McAloon, A., F. Taylor, W. Yee, K. Ibsen, and R. Wooley. 2000. Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks. Natl. Renewable Energy Lab. Tech. Rpt., NREL/TP-580-28893. <http://www.ethanol-gec.org/information/briefing/16.pdf>.

Mielenz, J.R. 1997. Feasibility studies for biomass-to-ethanol production facilities in Florida and Hawaii. Renewable Energy 10(2/3):279–284.

Odio, C. 1996. d-Limonene recovery. Citrus Eng. Conf. 42:45–54.

Stevens, C. 2007. DOE selects six cellulosic ethanol plants for up to $385 million in federal funding. US Dept. of Energy, Washington, DC. <http://www.energy.gov/news/4827.htm>.

Wilkins, M. R., Widmer, W. W., Grohmann, K. and Cameron, R. G., 2007. Hydrolysis of grapefruit peel waste with cellulase and pectinase enzymes. Bioresource Technol. 98(8): 1596–1601

Wilkins, M.R., Suryawati, L., Maness, N.O. and Chrz, D., 2007. Ethanol production by Saccharomyces cerevisiae and Kluyveromyces marxianus in the presence of orange-peel oil. World J. Microbiol. Biotechnol. 23:1161–1168.

Wooley, R., M. Ruth, J. Sheehan, K Ibsen, H. Majdeski, and A. Galvez. 1999. Lignocellulosic biomass to ethanol process design and economics utilizing co-current dilute acid prehydrolysis and enzymatic hydrolysis current and futuristic scenarios. Natl. Renewable Energy Lab. Tech. Rpt., NREL/TP-510-26157. <http://www.nrel.gov/docs/fy99osti/26157.pdf>.