2

Integrated Biosystems for Lignocellulosic Waste Management

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Scientists engaged in lignocellulosic research have developed biotechnologies for generating single products like sugars, ethanol, biofuels, high value biochemicals, etc., either by employing microbes or enzymes in bioconversion reactions. Considerable effort has also been put into making the process economically viable by optimizing the process conditions. However, for total mineralisation of the complex biomass with zero waste and zero emissions, several biotechnologies are to be combined in a specific sequence so as to evolve an integrated biosystem. Lignocellulose is one part of the complex biomass that requires to be released before being employed in a bioprocess. Indiscriminate and incomplete utilization of lignocellulosic material from total biomass will amount to tremendous wastes in resources and energy. The trend now is to integrate individual bioprocesses and come out with biotechnologies that are multi-product adhering to the zero waste/ zero emission concepts. Such an integrated approach would not only be ecofriendly and yield substantial profits but also ensure total recycling of biomass, complete mineralisation and minimum pollution. In this chapter we suggest how to blend biotechnologies to be in tune with nature's way of balancing carbon, nitrogen and sulfur cycles that can sustain plant, animal and human life.

INTRODUCTION

Large amounts of lignocellulosic wastes pose an environmental pollution problem and unfortunately both developed and developing countries use the easiest option to get rid of this bulk by burning the biomass. The available technology suggests that biomass containing lignocellulosic materials represents an abundant and inexpensive source of sugars that can be microbiologically or enzymatically converted into industrial products (Howard *et al.,* 2003). Effective bioconversion requires an intimate understanding of the composition of the starting material that varies with the source from which it is derived. Lignocellulose is a complex of polysaccharide micro fibers most often formed by cellulose and hemicellulose filaments and covered by lignin layers. The lignin stabilizes

DETOXIFICATION METHODS

To start with, it would be ideal if the formation of inhibitors during hydrolysis were avoided. A combination of mechanical and enzymatic treatments for the biodegradation of lignocellulosic material could achieve this, primarily due to the fact that enzymes are substrate-specific. But when chemical hydrolysis is resorted to, a number of byproducts are formed and detoxification by pretreatment and neutralization of pH are essential before lignocellulosic hydrolysates are used for microbial fermentation. A variety of biological, physical and chemical techniques have been proposed to reduce the concentration of the inhibitors in lignocellulose hydrolysates (Mussatto and Roberto, 2004). However, it must be emphasized that there is no universal method for detoxification of lignocellulosic hydrolysates since the efficiency of any detoxification method depends both on the composition of the raw material used and the hydrolysis conditions employed. For example, vacuum evaporation is a method that could reduce the content of volatile compounds such as acetic acid, furfural and vanillin (Rodrigues *et al.,* 2001). But this procedure increases the concentration of non-volatile toxic compounds and consequently the degree of fermentation inhibition. Precipitation of toxic compounds, ionization of inhibitors by changing pH (Martinez *et al.,* 2000, 2001) and physical adsorption on substances like activated charcoal (Mussatto and Roberto, 2001) could be low-cost, yet effective, additional routes of detoxification. An alternative tactic would be to develop species of microorganisms able to resist inhibitors so that they could be employed in bioconversion processes. Besides naturally occurring microorganisms, some thermophilic anaerobes and recombinant bacteria have been tried for direct microbial conversions. The latest trend is the use of new metabolically engineered microbial species that can better tolerate inhibitors and decrease the need to detoxify hydrolysates (Taherzadeh *et al.,* 2000). But it may still become necessary to convert toxic compounds into products that do not interfere with metabolism.

DIVERSITY OF BIOPRODUCTS

Several technologies are currently available for bioconversion of lignocellulose to a whole range of chemicals and/or value added products. These technologies continue to receive the attention of scientists and with the passage of time, it is expected that newer and improved quality products would be delivered at incredibly low prices. To make the product even more competitive, the industrial units are concentrating on agricultural and other cheap sources of raw material. Simultaneously, improvements in technologies are being attempted at all the levels of production, namely, process design, system optimization and model development. The industrial applications of some of the products generated through bioconversion of lignocellulosic material are consolidated in Table 1. The ever-increasing demand for bioproducts leads to over utilization of biomass that ultimately culminates in the accumulation of wastes. We need to address this issue using clean and ecofriendly technologies and one way to achieve this would be through integrated biosystems.

Table 1. Some industrially important products derived from lignocellulosic material

Starting material	*Products*	*Application*	*Reference*
Biomass	Lignocellulose	Pulp & Paper	Breen and Singleton, 1999.
Lignocellulose	Lignin	Process fuel	Crawford *et al.,* 1984; Kuhad and Singh, 1993.
Lignin	Aminolignin	Sorption active material for dyes, heavy metals, phenol, enterosorbtion	Verkhanovsky *et al.,* 1982a; 1982b; Dizhbite *et al.,* 1999.
Lignin	Vanillin Gallic acid	Herbicide, anti-foaming agents, anti-microbial agent, drugs	Ribbons, 1987. Delgenes *et al.,* 1998;
Hemicellulose (xylose)	Xylitol	Sweetener, Teeth hardening Anti-microbial agent	Parajo *et al.,* 1998.
Hemicellulose (arabinose, xylose, etc.)	Furfurol	Furfural-phenol plastics, varnishes, pesticides	Gravitis *et al.,* 2004.
Cellulose (glucose)	Ethanol	Chemical feed stock, octane enhancer, petrol additive	Kuhad and Singh, 1993; Ingram and Doran, 1995; Lee, 1997; Kuhad *et al.,* 1997; Chandrakant and Bisaria, 1998; Millati *et al.,* 2005
Lignocellulose	Residual lignified product from ethanol production	Co-product for industrial feedstock, nutritional antioxidants, ultraviolet absorbers, resins.	Anderson *et al.,* 2005

COMPOSTING OF LIGNOCELLULOSIC WASTES

The microbiological process of composting lignocellulosic materials arises due to the combined activities of a succession of a mixed microbial population. During this microbial succession, each type of microbe is suited to one specific condition of short duration and is only active in decomposing one type or group of organic matter present (Wong *et al.,* 1990). Ultimately, organic material is converted into carbon dioxide, humus and heat by compost microorganisms. Although it would appear that lignin could be degraded or extensively transformed during composting, the lignin loss in compost environment is hardly due to extensive mineralisation. Lignin degradation in composts is regulated by temperature, the original lignin content and the thickness of material. The organisms most efficient at mineralising lignin do not survive the thermophilic phase of composting and thus cannot play any significant role in mineralisation (Tuomela *et al.,* 2000). However, from literature it is evident that lignin could be degraded by thermophilic microorganisms. The idea is not merely to degrade lignin but to make sure that the process yields another product of commercial

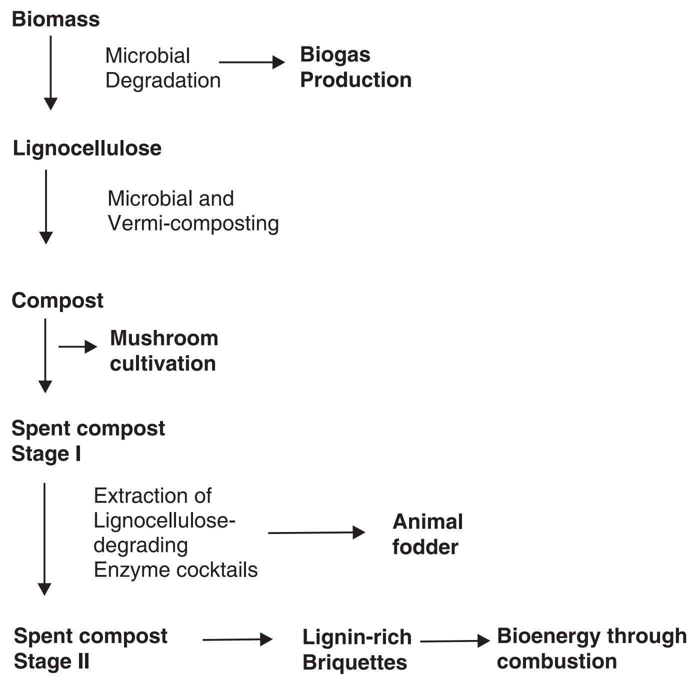

Fig. 1. A commercially viable pathway for integrating biosystems towards attaining zero waste.

ENERGY PRODUCTION FROM LIGNOCELLULOSIC WASTES

Biomass combustion is the oldest and most popular method for energy production. Besides combustion, other technologies of the thermal conversion of biomass for energy production include gasification, liquefaction and pyrolysis. The advantages of the combustion method for waste treatment are an approximately 10-fold decrease in waste volume, the reduction of the risk for soil and water pollution and the recovery of the heat formed. Although the direct combustion of biomass for energy production is undoubtedly, rather attractive, a considerably higher economic effect can be reached by a multistage biomass conversion. A considerable share of bioenergy is now substantially contributing to the total energy balance of many countries owing to the high energy yielding combustion of lignin-containing wastes. After calculating the economics including labour and water, the feasibility of large-scale lignocellulose-based bioenergy production in a renewable intensive global energy scenario (RIGES) has been aggressively advocated (Berndes *et al.,* 2001). It has been estimated that the energy of 1 kg of lignin is roughly equivalent to that of 0.6 kg of oil. At present special attention is paid to the production of fuel briquettes and granules with and without binders. Briquettes and granules are also produced using energy additives (coal siftings, mazut, organic materials etc). When we talk about integrated biosystems for energy production while preparing these briquettes and granules, we need to think in terms of mixing lignocellulosic wastes with

Senta, 2001). Bio-refinery technologies could generate value-added products that might range from basic food ingredients to complex pharmaceuticals and from simple building materials to complex industrial composites. The principal advantage of bio-refinery in comparison with oil refinery and other fossil fuel consumption systems is that biomass is renewable and a sustainable resource. To provide a complete wood and non-wood plant biomass refinery into value added chemicals, materials and biofuels, an integrated processing scheme has been recently proposed (Gravitis *et al.,* 2004). It allows producing a variety of products such as furfural, acetic acid, glucose, bioethanol, levoglucosan, microcrystalline cellulose, fibre materials, plastics, carbon materials, charcoal activated carbon and others (Tengerdy and Szakacs, 2003). A part of the lignocellulose bulk produces gas (Ekwenchi *et al.,* 1990) and the unused part of lignin are burnt in a boiler house to allow biomass processing with energy. Biogas has a slightly higher calorific value than natural gas and can be used to run generators for electricity production as well as cooking in households. It is advisable to resort to biogas production through anaerobic digestion to remove the ever-increasing infectious disease outbreaks especially in tropic developing countries. The strict anaerobic conditions required for a successful methane production kills most pathogens responsible for infectious diseases. This can not only remove the health hazard but also produce energy and promote aquaponics. The solids can be used as fertilizers directly or through composting which will ultimately improve and regenerate the microbial population in the soil, crucial for natural cycles of matter.

Structuring diverse industries into integrated clusters would essentially mean that the waste of one industry becomes the raw material for the next so that we are left with zero emissions (no waste in the air, water and soil). In addition, what is treated as waste in one chain of production is converted into value-added inputs in another. Products or part of them are also used as intermediary products for further processing into products of higher added value. The net result being the manufacturing line becomes a series of production cycles and recycling systems. Such an integration of various production systems facilitates increasing the diversity of value added products, competitiveness and solves environmental problems (Chang, 1987).

From Concept to Implementation

Several projects have been undertaken to fully exploit renewable resources and replace monoculture/ mono-product farming with a multi-product system all over the globe. Each of these is tailored to the demands of the society in which it operates and differs from country to country. The Montfort Boy's Town school in Fiji has set up an excellent fully operational integrated biosystem for us to observe and emulate. The established fish farming industry and its main economic resource, sugar were the base upon which the integration was designed and built. The system has now evolved to comply with a near zero waste/zero emission level.

Tropical countries have a great opportunity to use their abundant lignocellulosic wastes to their advantage using the biotechnologies enumerated above. Several strategies that are in use for converting these wastes into useful products and byproducts have been reviewed and discussed. No doubt, ongoing research is going to ensure that the processes become more and more profitable. But it would be ideal if a scheme for clustering of processes is developed wherein multiple products are generated from a single raw material. We propose here an integrated model system (Figure 2) for

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