PROSPECTS FOR THE COMMERCIALIZATION OF THE BIOSYNTHESIS OF MICROBIAL CELLULOSE

DONALD G. WHITE and
R. MALCOLM BROWN, JR.
Department of Botany
University of Texas
Austin, Texas 78713, USA

SYNOPSIS

Commercial applications of microbially derived cellulose have only recently been explored. Cellulose biosynthesis by the bacterium *Acetobacter xylinum* has distinctive advantages over traditional sources: no delignification is required following harvest; the product can be synthesized directly into an extremely strong non-woven "textile" of virtually any shape; the physical properties of the cellulose such as crystallinity, hydrophilicity, and degree of polymerization, can be controlled during synthesis; and, the cellulose can be produced from a wide variety of substrates. The ability to alter physical characteristics of the cellulose *in situ* may provide an efficient method for producing a broad array of value-added products. The development of a commercially feasible fermentation system for producing *Acetobacter* cellulose presents a significant technological challenge. Large-scale fermentation is complicated by a number of phenomena associated with the biology of acetic acid bacteria including strain instability, the synthesis of gluconic acid as a significant by-product, and poor oxygen diffusion through the cellulose product of this strictly

aerobic bacterium. Pressure-cycle or dual hollow fiber (DHF) fermenters may eliminate or reduce many of the problems encountered in producing large quantities of microbial cellulose. Further commercialization of *Acetobacter* cellulose will depend upon the successful integration of various technical and economic elements including market requirements, end-product characteristics, fermenter design and operating conditions, cost and availability of substrates, and geographic location. The ultimate promise of *Acetobacter* is the ability to take advantage of the rich scientific and technological knowledge base associated with it for the development of a commercial scale cell-free cellulose biosynthetic system. Such a system might allow the production of an even wider variety of cellulose based products with even greater efficiency, thus preserving valuable natural resources.

INTRODUCTION

Cellulose is synthesized by diverse organisms, ranging from multicellular and unicellular plants to bacteria. Currently, the primary industrial sources of cellulose are limited to the products of multicellular plants such as hard and softwood trees, cotton, flax, jute, ramie, and hemp. Of the several genera of bacteria known to synthesize cellulose, including *Sarcina*, *Agrobacterium, Rhizobium* and *Acetobacter* [1], only *Acetobacter* species produce cellulose in sufficient quantities to warrant commercial interest. Although the cellulose synthesizing capability of *Acetobacter xylinum* has been documented for over 100 years and has been the subject of extensive study [2,3,4,5], there has been only limited commercial application of this capability. There are unconfirmed reports of bulk production of *Acetobacter* cellulose in Germany prior to World War II. Currently, the only commercially available product of microbial cellulose is Nata, a food product of the Philippines [6]. Nata represents a relatively trivial application of *Acetobacter* cellulose and one which does not fully capitalize upon the commercial potential for the material. *Acetobacter* cellulose possesses a number of physical properties including high polymer crystallinity and high degree of polymerization which distinguish it from other forms of cellulose. By virtue of its mode of production, the hydrophilicity, tensile strength, and opacity of *Acetobacter* cellulose can be altered to suit many commercial applications. The relatively high cost for producing the cellulose may limit its application to high value-added products. In addition, the efficient, large scale commercial production of *Acetobacter* cellulose is complicated by the

biology of the bacterium and will require the application of new fermentation technologies such as the pressure-cycle or dual hollow fiber (DHF) fermenters. With an increased recognition for the advantageous properties of *Acetobacter* cellulose and the integration of business and economic factors involved in its commercialization, many other commercial applications may soon be developed.

FEATURES OF *ACETOBACTER* CELLULOSE

With the substantial sources of cellulose available, what is the value of a new source? The advantages of microbial cellulose lie in its unusual characteristics and its mode of production. These characteristics include:

- no delignification required during processing
- very high hydrophilicity in the never dried form
- capability of being directly synthesized into an extremely strong "microwoven" textile of any size or shape
- outstanding shape retention
- synthesis from a wide variety of substrates
- physical properties of the cellulose can be controlled during synthesis

No Delignification

Cellulose from the cell walls of woody plants is formed in close association with lignin, hemicellulose, and other compounds. For many applications, such as in paper manufacture, wood cellulose must first be delignified by an extensive process known as pulping. Depending upon the process employed, pulping requires four or five processing steps [7] following logging to obtain a partially purified cellulose material (fig. 1). In contrast, *Acetobacter xylinum* synthesizes an extracellular ribbon of nearly pure cellulose directly into the incubation medium. The ribbons of individual bacterial cells interweave to form a hydrophilic cellulose membrane known as a pellicle (fig. 2). The production of relatively high yields of *Acetobacter* cellulose without the corresponding synthesis of lignin and hemicelluloses greatly facilitates the process required to purify the cellulose. Nearly all of the cellular biomass and incubation medium components can be efficiently removed from the pellicle by a simple cleaning process (fig. 1). If necessary, the pellicle can then be dried by various means as

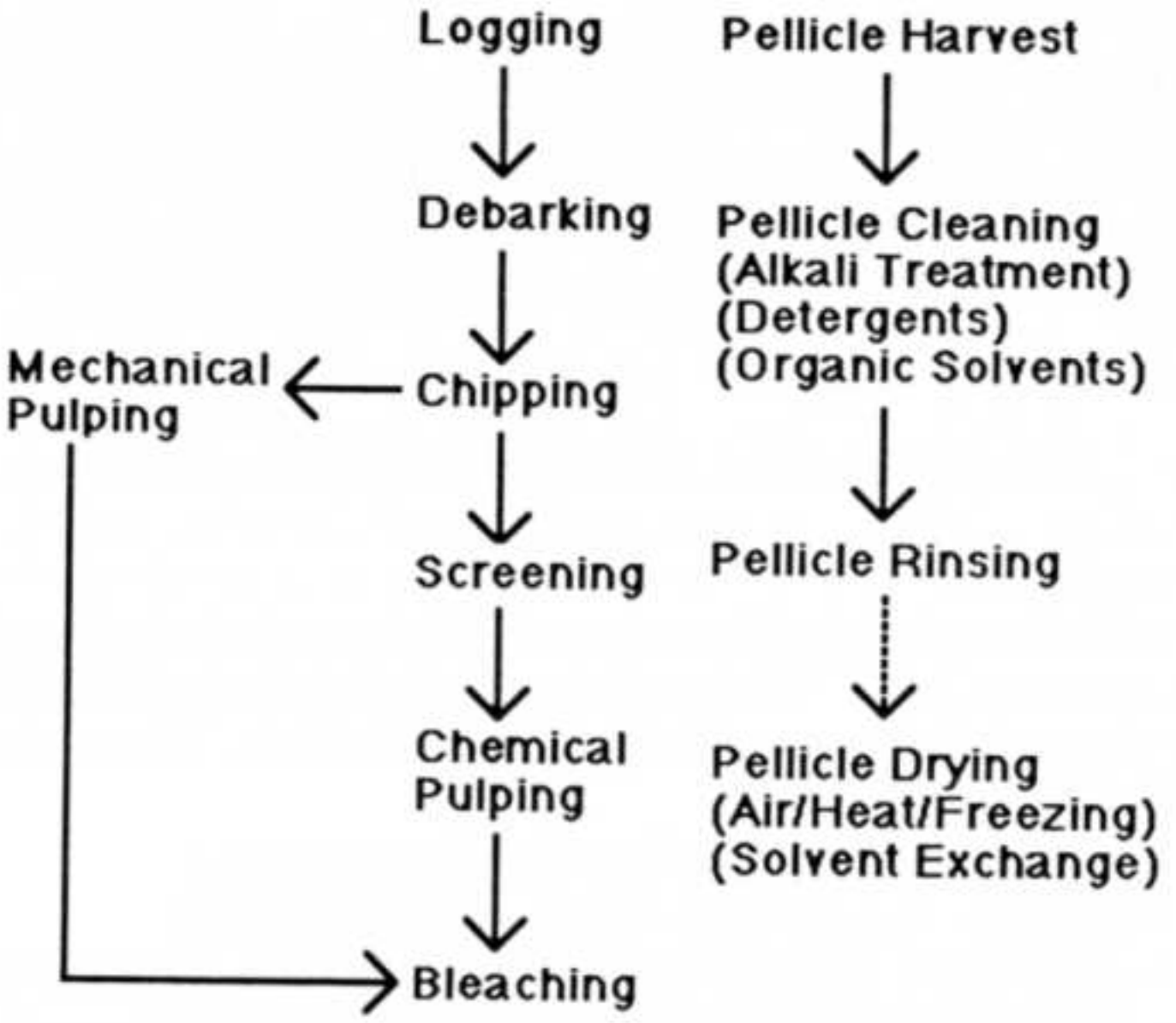

Fig. 1. Comparison of typical pulping processes for purification of cellulose from wood with a cleaning process for *Acetobacter* cellulose pellicles.

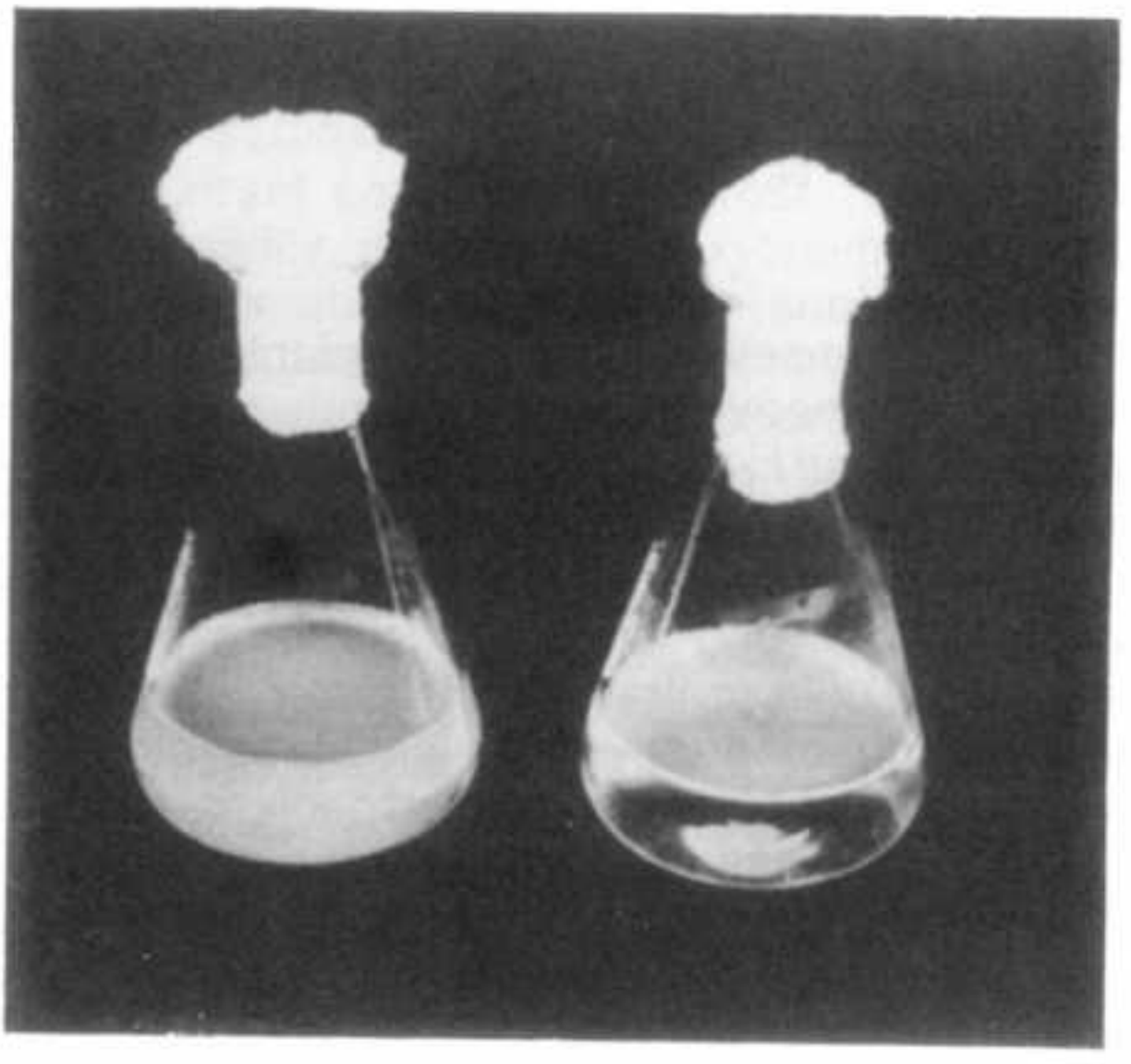

Fig. 2. The formation of a cellulose pellicle at the air/liquid interface by *Acetobacter xylinum* incubated on Schramm-Hestrin medium [24].

required for a particular end product use. The simpler cleaning process of *Acetobacter* cellulose may result in higher end product yields with greater purity than can be obtained by the pulping process required for woody cellulose products.

Outstanding Hydrophilicity

The native *Acetobacter* pellicle, in its never dried state, has outstanding hydrophilicity. Depending upon synthetic conditions, it may have a water holding capacity ranging from 60 to 700 times its dry weight [16]. The hydrophilicity of the cellulose pellicle is due in part to the extensive interior surface area of the interstitial spaces of the never dried pellicle/ribbon matrix. The presence of pore structures and "tunnels" within the wet pellicle may be the reason for its rapid uptake of post synthetic processing agents or dyes [8]. Other sources of cellulose, such as cotton and wood, enter the manufacturing process in a more compacted form. This form is not only less hydrophilic than microbial cellulose but is also less susceptible to chemical treatments or to dye uptake. As a consequence, harsher physical and chemical processing is required, reducing cellulose yields and increasing processing costs.

Moldability

The strictly aerobic nature of *Acetobacter* may lend itself to industrial application. In undisturbed cultures, *Acetobacter* forms the cellulose pellicle at the air/liquid interface. Through the use of gas permeable molds, "microwoven" textiles of virtually any shape can be produced [9]. It has been demonstrated that a molded, seamless fabric in the shape of a glove can be formed *in situ* by an active *Acetobacter* culture (fig. 3). These microbial textiles can be synthesized into extremely thin, pliable forms which are gas and liquid permeable.

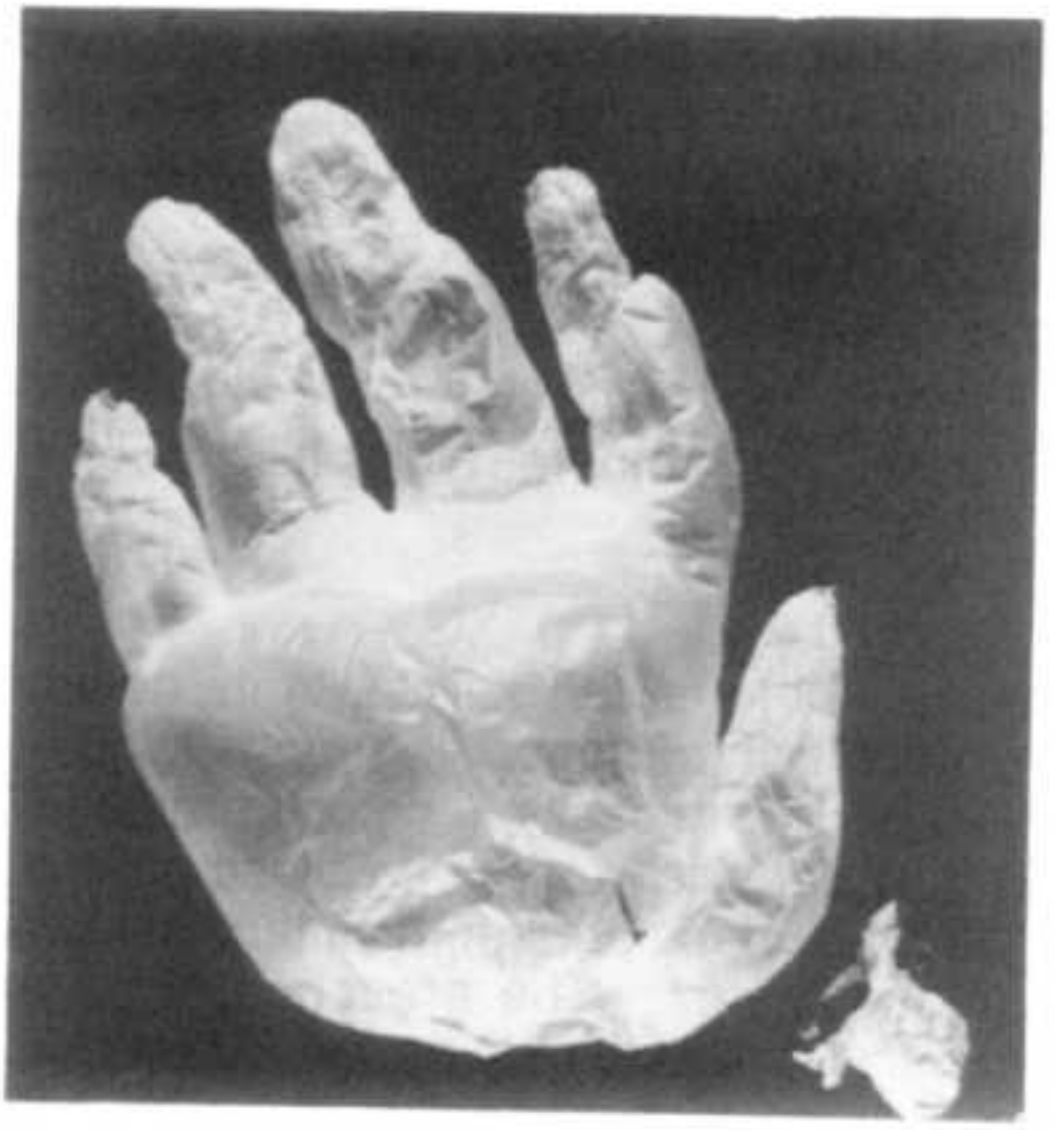

Fig. 3. Dried *Acetobacter* cellulose formed into a seamless glove shape *in situ* during cellulose biosynthesis.

Excellent Shape Retention and Tensile Strength

The native *Acetobacter* pellicle has mechanical properties, including shape retention and tear resistance, which are superior to many synthetic fibers. It has been reported that following heat and pressure treatment, microbial cellulose has a Young's Modulus (a measure of shape retention) of 30 Giga-Pascals, 4 times greater than any organic fiber [10,11]. The same report indicates that the tensile strength (tear resistance) of the treated material is five times greater than polyethylene or vinyl chloride films. Sony Corporation (Japan) has taken advantage of the shape retention properties of the treated *Acetobacter* cellulose in the development of a high fidelity audio speaker diaphragm made from the material [10,11]. The Ajinomoto Company (Japan), a collaborator with Sony in the development of the cellulose treatment process, has begun distributing samples of ultra-high strength paper manufactured from *Acetobacter* cellulose [10,11].

Broad Substrate Utilization

Acetobacter xylinum is capable of producing cellulose from a variety of inexpensive carbon substrates. Widely available commodity sources of carbon which may be utilized by *Acetobacter* include dextrose (glucose), sucrose, fructose, invert sugar, ethanol and glycerol [12,13]. This diversity of utilizable substrates provides considerable flexibility in the location of the manufacturing facility since at least one of these substrates is produced in virtually every region of the world. The availability of inexpensive cane sugar and coconut milk (as a by-product of coconut production) in the Philippines is a major economic factor in the commercialization of Nata products. Flexibility in the manufacturing process is enhanced by the ability to substitute among a variety of possible fermentation substrates and provides some independence from impact of price increases for an individual substrate. The ability to employ a substrate diversification strategy is particularly advantageous in view of the significant price volatility associated with international agricultural commodity products.

Control of Physical Properties During Synthesis

A major advantage of *Acetobacter* cellulose technology lies in the ability to control the physical characteristics of the native cellulose as it is being synthesized. Previous investigations have demonstrated that the addition of direct dyes such as Congo Red, fluorescent brightening agents such as Tinopal LPW, and carboxycellulose derivatives to the *Acetobacter* culture can alter the assembly of the cellulose ribbons [14,15]. Depending upon the agent employed and its concentration, a variety of cellulose structures can be produced. The variation in these structures can range from individual microfibrils that are loosely associated into ribbons to completely disassociated fibrillar structures, resulting in amorphous cellulose. The extension of this earlier research has resulted in the development of a proprietary process which can significantly effect the absorptive properties of *Acetobacter* cellulose. This process enables nearly complete rehydration of the pellicle to its original hydrophilicity even after three cycles of wetting followed by drying at elevated temperatures [16]. It may be possible that *Acetobacter* cellulose synthesized by this process can be used as a reusable super-absorbent material.

The ability to control the cellulose synthesis process within a closed system provides several advantages. It enables the manu-

facturer to alter the properties of the microbial cellulose to a greater degree than would be possible by post synthetic processing of other sources of cellulose. By manipulating the cell density, incubation conditions, fermentation vessel configuration, and media components, the opacity, strength and pliability of the harvested cellulose product can also be controlled. It may be possible to control the degree of polymerization of the cellulose as well [17].

COMMERCIAL APPLICATIONS FOR *ACETOBACTER* CELLULOSE

The ability to alter the hydrophilic and mechanical properties of cellulose during polymer synthesis provides the basis for the development of a broad array of value-added products. The uses for modified microbial celluloses range from stable, heat sterilized, non-caloric food emulsifiers to rewettable, super-absorbant pads. By adjusting the culture growth conditions, the texture of raw microbial cellulose can be varied substantially. Modified celluloses derived from woody plants are currently used as non-caloric bulking additives in many soft/semi-liquid foods [18]. These materials tend to have a pronounced "gritty" texture [19]. Due to the extensive processing required to render these celluloses more hydrophilic, they are only available as fine powders or slurries which limits their usefulness as texturizers for solid foods. With *Acetobacter* cellulose, it may be possible to manufacture food products with textures ranging from a gelatinous material, which provides the appeal of Nata, to denser forms which may be used as a base material for synthetic meat, fish, or poultry products. The extensive internal surface area of the native pellicle, combined with its high wet strength and relatively low chemical reactivity make it a good candidate as a support material for catalytic agents. The ability to alter the porosity of the cellulose may lend itself to the development of membranes with a variety of permeabilities. The preparation and use of *Acetobacter* cellulose in dynamic osmometer membranes has been previously described [20]. The shape retention of microbial cellulose could be used in applications in addition to audio speaker diaphragms, where stress and strain fatigue is a factor.

Broadened commercial interest in *Acetobacter* cellulose appears to be well underway. Ajinomoto has announced plans to begin mass production of *Acetobacter* cellulose in 1988 [11]. In addition to Ajinomoto and Sony, several other firms are known to be developing commercial applications for *Acetobacter* cellulose. Du Pont has been developing a process for wet spinning *Acetobacter* cellulose into textile fibers [21]. Both Biofill-Indústria e Comércio de Produtos Biotecnologicos (Brazil) [22] and Johnson & Johnson [23]

have or are developing wound care products utilizing *Acetobacter* cellulose. Presumably, the products exploit the hydrophilic and wet strength properties of the cellulose. The international nature of the current commercial interest in *Acetobacter* cellulose and the diversity of products under development exemplify the broad range of potential applications which are possible for *Acetobacter* cellulose.

The successful commercial application of *Acetobacter* cellulose technology will require that it create or extend markets for cellulosics rather than attempting to merely substitute for existing cellulose products. While microbial cellulose may be useful in numerous applications where purity, hydrophilicity, or mechanical strength are required, its high cost of production may limit its application to a much smaller range of value-added products. As of May, 1987, Ajinomoto sold 1 kilogram samples of wet *Acetobacter* cellulose for 1,000 yen, or approximately $160/kg. dry [10]. This price is over one hundred times greater than the prices of either wood pulp or raw cotton. Obviously, microbial cellulose cannot presently compete with these sources of cellulose solely on the basis of price. Although significant cost reductions are possible by improvements in fermentation efficiency and economies of scale, the lower limit on the cost of microbial cellulose is determined by the price of the raw material substrates. The prices of these inputs are generally in the same range as the other commonly available sources of cellulose such as wood pulp or cotton. Consequently, *Acetobacter* cellulose may always be more expensive to produce than conventional sources of cellulose. For this reason, the successful commercialization of *Acetobacter* cellulose will depend upon the careful selection of applications where its superior performance can justify its higher cost. Audio speaker diaphragms and wound care products represent model applications for *Acetobacter* cellulose. In both cases, the advantage of the unique combination of physical properties of the cellulose outweigh its higher cost.

BIOTECHNICAL FACTORS INVOLVED IN THE COMMERCIALIZATION OF *ACETOBACTER* CELLULOSE

While the characteristics of *Acetobacter* cellulose present outstanding commercial potential, the large-scale commercialization of this material poses several biotechnical challenges. The efficient, large scale production of *Acetobacter* cellulose is complicated by several

phenomena associated with the biology of the organism and available fermentation technology. Among these are:

- instability in the phenotypic expression of cellulose synthesis in *Acetobacter*
- synthesis of large quantities of gluconic acid as by-product of carbohydrate metabolism, particularly glucose
- poor mass transfer through the insoluble cellulose product which complicates fermenter design

Strain Instability with Respect to Cellulose Synthesis

The extreme variability in the phenotypic expression of cellulose synthesis by individual *Acetobacter* cells isolated from shaken or swirled cultures has been well documented [24,25,26]. The presence of substantial numbers of pellicle deficient variants significantly reduces the cellulose productivity of a culture, particularly if it is operated as continuous or semi-continuous fermentation. Since it is possible that environmental factors such as pH, oxygen concentration, or other metabolites may be responsible for the appearance of these variants, further investigation into the cause of this phenomenon is certainly warranted. It may then be possible to develop a fermentation process which would reduce the frequency of the pellicle deficient variants to the point where cellulose can be produced efficiently on a continuous, industrial scale basis. Alternatively, it may be possible to select for or mutagenize a strain which exhibits a stable cellulose synthesizing phenotype under industrial fermentation conditions. The Cetus Corp. has filed a patent application which claims the development of a strain of *Acetobacter* which remains stable with respect to colony morphology under agitated culture conditions [27].

Gluconic Acid Formation

Another aspect of *Acetobacter* biology, the production of gluconic acid, must also be addressed prior to the development of large scale fermentation system. Cellulose synthesizing strains of *Acetobacter* typically produce gluconic acid as a byproduct of carbohydrate metabolism, particularly when dextrose is the substrate. When *Acetobacter xylinum* is grown on a dextrose substrate (or a carbohydrate substrate of which it is a component), it has been observed to convert 26% of the glucose into gluconic and 2-keto-gluconic acid [27]. Much of the gluconic acid has been shown to be subsequently

recycled into cellulose and other cellular metabolites [28,29]. Despite its ultimate utilization by the culture, the inhibition of gluconic acid pathway would be advantageous in industrial fermentations. The formation of significant amounts of acid by an active *Acetobacter* culture makes pH control of the fermentation difficult, particularly in batch and semi-continuous cultures. The over production of gluconic acid by *Acetobacter* grown in batch cultures makes it very difficult to precisely determine the pH range for maximizing the rate of cellulose synthesis. The pH of an *Acetobacter* batch fermentation has been observed to vary over time from 3.5 to 6.2 [30]. Consequently, the fermentation may be operating within the optimal pH range for cell division and/or cellulose synthesis for only part of the fermentation cycle.

It is also possible that during carbohydrate metabolism, the diversion of primary substrate into gluconic acid reduces the availability of the most easily metabolized substrate. Cetus Corp. has developed a strain of *Acetobacter xylinum* with reduced gluconic acid synthesizing function that produces cellulose at a higher rate than the wild-type *Acetobacter* [27]. This observation suggests that the presence of a gluconic acid shunt in *Acetobacter* reduces the overall rate of cellulose formation by the culture. It has not been determined if the reduction in the rate of cellulose synthesis in batch cultures is due to a difference in cell division rates and/or if gluconic acid has a direct effect on the kinetics of cellulose biosynthetic pathway. For an industrial fermentation, the relative importance of these effects and the ability to affect them will have a major impact on the selection of a fermenter configuration. In batch fermentations, the overall rate of cellulose formation is determined by two relatively independent factors; the rate at which the producing cell mass increases and the kinetics of cellulose biosynthesis at the cellular level [31,32]. For semi-continuous and continuous fermentations, only the kinetics of cellulose biosynthesis at the cellular level is limiting. Therefore, it is important to attempt to isolate gluconate reduced or deficient strains of *Acetobacter* and to determine their rates of cell division and cellulose synthesis relative to gluconate producing strains prior to the selection of bacteria and fermenter combination.

The Cellulose Pellicle as a Barrier to Mass Transfer

As a strict aerobe, *Acetobacter* has an absolute requirement for oxygen in order to maintain active metabolic function. The synthesis of an insoluble extracellular pellicle by *Acetobacter xylinum* may create a significant barrier to oxygen diffusion within the growth medium. Nata cellulose is currently synthesized in static culture fermentations [6]. In

standing cultures, essentially all cellulose synthetic activity occurs at the air/liquid interface [33]. Consequently, the surface area of the air/liquid interface must be maximized at the expense of volume in order to achieve maximal rates of cell growth and cellulose synthesis. The application of this fermentation technique is satisfactory for the production of cellulose for use in its original wet state, as in the Nata food products. However, the surface area required to synthesize cellulose on a dry weight basis is enormous. We have estimated that a standing batch culture would require approximately 2,000 square feet of air exposure to sustain a production rate of one pound (dry weight) of cellulose per day.

The cellulose of *Acetobacter xylinum* also presents complications for deep tank batch fermentation processes. The cellulose product suspended in the culture may form an oxygen or nutrient deficient environment where the cellulose is in intimate association with the bacteria. A similar condition, found in shake batch cultures, tends to strongly select for the growth of pellicle deficient phenotypes. Agitation of the fermentation medium can improve the overall homogeneity of culture environmental conditions but may not be able to eliminate the barrier effect of the cellulose at the cellular level. The use of an impeller for culture agitation is further complicated by constant fouling of the impeller with the cellulose. An impeller may also cause significant shearing of the cellulose, decreasing the average length of the fibers.

A further complication of deep tank fermenters is the potential impact of the mixing technique on the physical properties of the cellulose pellicle. The effect of culture shaking on overall pellicle morphology has been well documented [24]. Spheroid masses of cellulose, with or without projections, are typically formed in shake cultures. The physical properties of the spherical pellicles have not been characterized and it is not known whether their physical properties differ from pellicles formed in still culture. A characterization of the effect of an impeller or other agitation techniques on the physical properties of the cellulose produced may be necessary if a deep tank fermentation is to be considered.

ALTERNATIVE FERMENTER CONFIGURATIONS

Pressure-Cycle Fermenter

An alternative to standing or deep tank batch culture techniques may be the adaptation of the pressure-cycle fermentation

technology originally developed by Imperial Chemical Industries (ICI) (Great Britain) [34]. Pressure-cycle, or "air lift" fermenter, originally designed for the production of single cell protein from *Methylophilus spp.*, may be suitable for the production of *Acetobacter* cellulose. High dissolved oxygen levels can be achieved within the pressure-cycle fermenter by using air under pressure to lift the bacterial culture through an air lift incubation chamber. The system consists of a loop reactor in which part of the culture is harvested at the top of the air lift while the remaining culture is depressurized, cooled, and mixed with fresh medium before returning to the air lift. The loop reactor configuration exposes the microorganism to some fluctuation in oxygen tension. This may complicate its adaptation to *Acetobacter* fermentations as it has been reported that production of acetic acid by *Acetobacter sp.* is highly sensitive to the oxygen level of the medium [35]. Consequently, the reactor will have to be configured so that the oxygen tension minima during the pressure cycle is sufficient to maintain a productivity of the culture.

Dual Hollow Fiber Bioreactor

The development of a membrane bioreactor fermentation system could provide another method for the large-scale production of *Acetobacter* cellulose. Membrane bioreactors are based upon the application of gas and/or liquid permeable and semipermeable membranes to aerobic fermentation systems. The permeable membranes allow the diffusion of oxygen and nutrients through the culture containment walls of the fermentation vessel. The continuous circulation of fresh substrates within the membranes enables the culture to operate constantly at or near optimal culture conditions for the synthesis of the desired product.

Bioreactor systems consisting of silicone and polypropylene hollow fibers have been developed for immobilizing metabolically active, aerobic cells [36]. On a laboratory scale, Dual Hollow Fiber (DHF) systems have been used to produce rifamycin B from *Norcardia mediterranei* and for the conversion of acrylonitrile to acrylamide by *Brevibacterium* sp. [37]. Although this bioreactor system has never been applied to the production of an insoluble bacterial product such as cellulose, experiments in our laboratory have demonstrated that cellulose can be synthesized by active *Acetobacter* cultures contained within small diameter silicone tubes [9].

The DHF bioreactor system could substantially improve the aeration of *Acetobacter* cultures in contact with the cellulose product.

The system can provide a continuous flow of nutrients and aeration to the culture without fluctuations in oxygen tension and the high energy consumption of the air lift fermenter. DHF system does not require the enormous surface area or the agitation devices necessary in static or deep tank fermentations. The partitioning of the gas and liquid medium from the cellulose synthesizing culture greatly increases the control over the fermentation system. It allows the fermentation to be operated at optimal conditions on a continuous basis and provides additional bioreactor flexibility for producing microbial celluloses with a variety of physical properties.

Both of the proposed fermentation systems, the pressure-cycle and the dual hollow fiber systems operate on a semi-continuous or continuous basis and consequently are more amenable to automation. In contrast to batch cultures, neither of these types of fermentations requires a complete regeneration of the cellular biomass each time the cellulose is harvested and therefore have an additional advantage of reducing time and nutrients required to generate the productive cell mass.

To date, the pressure-cycle fermenter has seen only brief commercial service and the DHF fermentation technology has not yet been applied on a large-scale commercial basis. These two fermentation technologies are considerably more complex than either the deep tank or still culture fermentation systems. The potentially higher construction and operating costs these new systems could offset any advantages they may have in substrate conversion efficiency or the rate product synthesis (throughput). Although more labor intensive, the static batch culture system as currently employed in the Philippines has the advantage of being much less costly to construct, and is simpler and more robust than the other two proposed systems. Ultimately, the selection of the type of fermentation system to be used will depend on the characteristics of the cellulose to be produced, the end use for the cellulose, and the comparative economics of each fermentation system for a given geographic location.

INTEGRATION OF ECONOMIC AND TECHNICAL ELEMENTS

The widespread commercialization of *Acetobacter* cellulose will depend upon successful integration of both economic and technical factors (fig. 4). The selection of product applications for *Acetobacter* cellulose will depend upon an evaluation of how the unique set of characteristics of the material can add sufficient value to justify its

significantly higher cost. With the determination of the appropriate product applications, the fermenter, fermentation substrates and adjuncts must be developed to produce *Acetobacter* cellulose with the appropriate characteristics. The cellulose end product characteristics, fermenter design and operation conditions, and substrates and media adjuncts are interactively related (fig. 4). The selection of substrates to be used for the industrial synthesis of cellulose invariably will be determined by their price and availability, both of which are affected by the geographic location of the facility. The type of fermentation process used is also directly affected by its geographic location. The comparative cost of labor and interest rates for capital will affect the relative levels of capital and labor intensiveness of the fermentation process (fig. 4). Similarly, the availability of skilled labor to construct and operate the facility may also affect the ultimate technological intensiveness of the fermentation system.

The production of the simple Nata products by a labor intensive, uncomplicated fermentation method using cheap, locally obtained raw materials illustrates the adaptive and interrelated nature of the various economic and technical factors. Technologically more complex *Acetobacter* cellulose-based products may soon be commercialized. These products will require an even tighter coupling

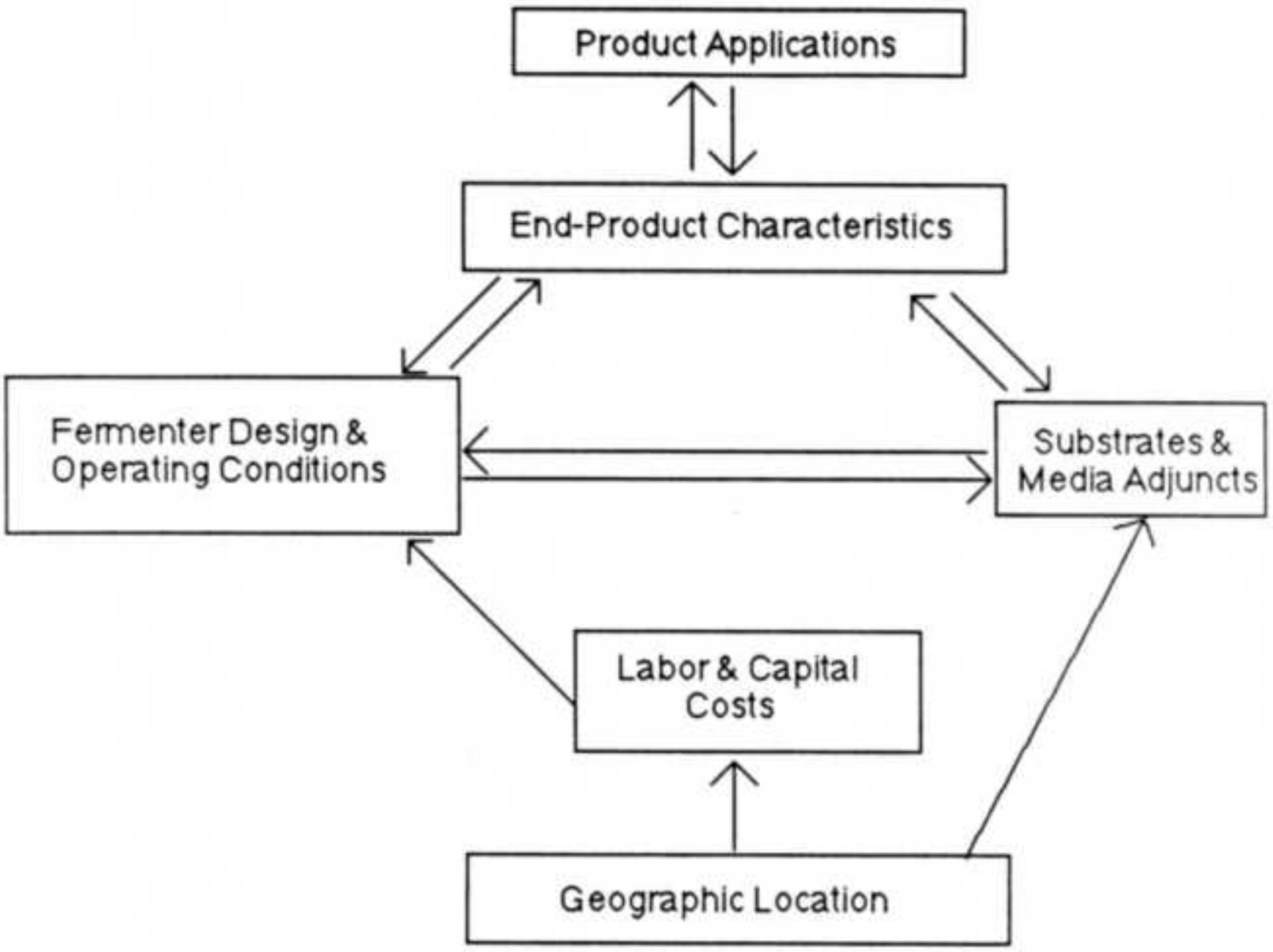

Fig. 4. Major interactive technical and economic elements involved in the commercialization of *Acetobacter* cellulose.

and balancing of the underlying technical and economic factors necessary for successful commercialization. Fortunately, the versatility of the material and the breadth of potential applications for *Acetobacter* cellulose suggests that at least a few of them will be able to overcome the economic and biotechnical hurdles to become commercially profitable products.

LONG-TERM PERSPECTIVE

The near term outlook for the development of *Acetobacter* cellulose products appears favorable. The longer-term prospects for *Acetobacter* based cellulose biosynthetic technologies suggest even greater promise. Since the first recorded observations of cellulose biosynthesis in *Acetobacter* , this microorganism has served as a model system for the study of cellulose biogenesis. As a result, a strong scientific and technological foundation for the commercialization of *Acetobacter* cellulose has been developed and maintained. Current investigations into the regulation of cellulose biosynthesis and biocrystallization may eventually lead to genetically engineered *Acetobacter* strains which are capable of synthesizing cellulose more efficiently and with specific physical characteristics. Perhaps the greatest potential for the system is the development of a completely abiotic system for the synthesis of cellulose. *Acetobacter* preparations have been used to develop *in vitro* system for the synthesis cellulose [38]. Recently, the purification of the cellulose synthase has been demonstrated [39]. Continued research in this area may eventually culminate in the development of a commercial scale cell-free process for the synthesis of cellulose in a manner analogous to the present day production of High Fructose Corn Syrup [40]. The development of a robust, well regulated cellulose synthesizing enzyme system would significantly reduce or eliminate the amount of cellular biomass necessary for the cellulose production. Cellulose could then be "manufactured" by this process with the efficiency necessary to compete with contempory sources of cellulose. The eventual substitution of *Acetobacter* derived cellulose for forest derived cellulose may provide more than just an economic bonus -- it could reduce or eliminate the destruction of native plant gene pools and preserve beautiful and ecologically important natural habitats associated with Earth's forest flora.

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