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Understanding the potential of bamboo fibers in the USA: A comprehensive techno-economic comparison of bamboo fiber production through mechanical and chemical processes

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Abstract: The growing interest in bamboo fibers for pulp, paper, and board production in the USA necessitates a comprehensive financial viability assessment. This study conducts a detailed technoeconomic analysis (TEA) of bamboo fiber production, primarily for the consumer hygiene tissue market although it is also applicable to other industrial uses. The economic viability of two pulping methods – alkaline peroxide mechanical pulping (APMP) and ammonium bisulfite chemical pulping (ABS) – was explored within three different pulp mill settings to supply pulp to two nonintegrated tissue and towel mills in South Carolina, USA. The target was to produce wet lap bamboo bleached pulp at 50% consistency and 70% ISO brightness. Despite higher initial capital invesment and operating costs, ABS achieved a lower minimum required selling price – USD 544 to 686 per bone dry metric ton (BDt = 1000 BDkg) – in comparison with USD 766 to 899 BDt^{-1} for APMP. This price advantage is partly due to an additional revenue stream (lignosulfonate byproduct), which not only boosts revenue but also circumvents the need for expensive chemical recovery systems. When compared with traditional kraft pulping, both methods require significantly lower capital investments, with minimum required selling prices (estimated to achieve 16% IRR) below current market rates for extensively used bleached kraft pulps in the USA tissue

[Correction added after first online publication on 06 July 2024; The author name “Camilla Abatti” has been changed as “Camilla Abbati de Assis”]

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industry. The economic benefits derive from several factors: the low cost of bamboo as raw material, reduced capital needs for new pulping technologies, lower transportation costs from the pulp mill to tissue and towel manufacturing facilities, and the high market price of bleached kraft pulp.

Key words: technoeconomic analysis; bamboo pulp; mechanical pulping; chemical pulping; minimum required selling price

Introduction

The USA pulp and paper industry encompasses a wide array of products, including paperboard, containerboard, packaging, hygiene tissue, and printing and writing papers.[1] Operating over 300 mills across the nation, this sector is pivotal in supplying important goods to the public, with a production output of 91 million finished short tons of paper and market pulp.[2] Particularly noteworthy within this sector is the hygiene tissue segment, which produces essential items such as toilet paper, paper towels, and facial tissues.[3] This segment predominantly utilizes 64% virgin wood fibers and 36% recycled fibers for the production of consumer hygiene products.[2] Nonetheless, the industry faces challenges related to the supply of recycled fibers, primarily due to the impacts of digitalization. This includes decreased availability and quality of recycled fibers, alongside price volatility.[4,5] Similarly, the sourcing of virgin fibers is hampered by significant price fluctuations in virgin wood costs.[6] At the same time, the global push towards sustainability has led consumers to demand more eco-friendly alternatives, with nonwood fibers being perceived as more sustainable options, although the validity of these claims varies.[7,8] In response, companies in the hygiene tissue sector are exploring alternative fibers, such as agricultural residues (e.g., wheat straw and sugarcane bagasse) and dedicated crops (e.g., bamboo and miscanthus), to navigate through current and anticipated disruptions in raw material supplies.[9–12]

Bamboo has been a papermaking fiber source for many years, predominantly in China and India.[13] It not only competes favorably with USA mixed Southern hardwood pulp in terms of quality but may also be lower in cost.[14] An extensive technical and financial model for bamboo plantations in the Southern USA determined that bamboo stands out as a compelling alternative raw material for the hygiene tissue industry, boasting a suitable selling price for bamboo chips delivered to pulp mill locations.[15] Regarding market acceptance, despite over 99% of hygiene tissue products being traditionally made from virgin or recycled wood fibers, bamboo toilet tissue is growing in the USA market.[16] This shift is primarily driven by consumer perception of bamboo as a more sustainable option.[17,18] However, a significant portion of bamboo-based products available in USA markets is imported mainly from China, either as finished products or market pulp.[19] The extensive transportation distance from China to the USA, and the predominant use of coal in Chinese pulp and paper manufacturing, significantly impact the carbon footprint of these goods.[2,20] Thus, the development of locally produced bamboo pulp in the USA may lead to a substantially reduced carbon footprint for nonwood fibers used in hygiene tissue applications.

To produce fibers from bamboo chips, three primary methods are employed: chemical (for example, kraft pulping), semi-chemical (such as sulfite process using various bases), and mechanical – namely, alkaline peroxide mechanical pulping (APMP). Each method results in fibers of varying qualities and performance.[14] The kraft pulping process is renowned for its long-term efficiency through a closed-loop system but it faces commercial challenges such as high capital investment and raw material limitations.[21,22] Nonwood raw material sources, including bamboo, present operational challenges in the kraft process due to their high silica and fines/parenchyma cell content impacting process efficiency and cost effectiveness.[23] Silica increases black liquor viscosity and causes fouling and clogging in evaporator, recovery boiler, and causticizer, leading to lime reuse/recycling issues, while fines/parenchyma cells reduce pulp drainage and slow down paper machine runnability.[24] Moreover, the low yield of the kraft process (45-55%)[25] compared with other high-yield processes like mechanical pulping (80-90%),[26] results in larger raw material collection and transportation costs. This increase in cost poses a challenge for nonwood large-scale commercial operations, making it impractical for kraft facilities, which must operate on a large scale to justify the significant capital investment required for greenfield mill projects.[27]

The ammonium bisulfite chemical pulping (ABS) process offers a viable alternative to the traditional kraft pulping method. This chemical variant of sulfite pulping uses bisulfite (HSO_3^-) produced from SO_2 and H_2O within a pH range of 2 to 6.[28] When nonwoods are pulped using this process, the resulting pulp demonstrates competitive performance in terms of properties and yield compared to kraft pulp.[29] A notable example of its application is in China, where companies like Shandong Tranlin Paper Co. utilize ABS to process wheat straw into pulp, showcasing the method's feasibility.[2] The byproduct of this process, known as spent red liquor, contains valuable lignosulfonates and sugars. These can be repurposed as fertilizers or soil amendments in agriculture, or converted into sugar-derived products like ethanol,[30–32] creating additional revenue streams.[33] In the case of lignosulfonate price, it depends heavily on the quality of the lignosulfonate obtained in the strong spent red liquor, which has been found to range between USD 250–500 t^{-1},[34] with the highest price associated with lignosulfonate suitable for premium applications. This potential for supplementary income can help to lower the minimum required selling price of the pulp, improving the financial outlook for pulp mills.[35] Furthermore, the ABS process eliminates the need for a chemical recovery boiler, required in kraft pulping, significantly reducing both capital investment and potential biogenic emissions.[1]

Pulp suitable for tissue applications can also be produced through mechanical pulping methods without extensive chemical changes and recovery units while preserving high yields (80%-90%).[26] Fibers obtained through a chemical process involve the dissolution of lignin but mechanical pulping uses mechanical energy to separate fibers while retaining most of the lignin.[36] To enhance the quality of the final pulp and decrease energy consumption, chips can be subjected to steam treatment or chemical pretreatment before defibration.[37] Alkaline peroxide mechanical pulping combines pulping and bleaching into a single-stage process by using different chemicals (e.g., sodium hydroxide, hydrogen peroxide, and chelating agents) in the pretreatment stage.[38] This high-yield process offers advantages such as low capital investment, attractive pulp strength and brightness, nonsulfur pulping, chlorine-free bleaching, lower energy consumption than other mechanical processes, and versatility in applying diverse raw materials.[39–41] Alkaline peroxide mechanical pulping has been conducted successfully on nonwood fibers such as wheat straw and sugarcane bagasse, reporting pulping yield and brightness up to 90% and 78% ISO, respectively.[42,43]

The existing literature on the technoeconomic analysis (TEA) of both chemical and mechanical processes for nonwood fibers is sparse. To date, research has yet to undertake a comprehensive comparison of the economic feasibility between chemically and mechanically processed bamboo pulp. This study aims to fill this gap by conducting a techno-economic analysis, evaluating the feasibility of producing bamboo pulp suitable for hygiene tissue applications in North America. Rather than producing a generic analysis, it was elected to develop specific cases, including:

1. Developing bamboo plantations on existing agricultural land located in South Carolina, USA.
2. Considering two distinct pulping processes: ammonium bisulfite chemical pulping (ABS) and alkaline peroxide mechanical pulping (APMP).
3. Targeting production of bleached pulp at 70% ISO brightness for delivery to one or more specific existing consumer tissue and towel mills located near the modeled bamboo plantations and the pulp-producing mills.

The outcomes of this research will offer crucial insights not only into the hygiene tissue industry but also for the production of other pulp and paper grades in the USA.

Materials and methods

The TEA of bamboo pulp developed in this study is based on three separate economic considerations:

1. Bamboo is planted on existing agricultural land by landowners or land renters who must absorb all costs of establishment, maintenance, growing, harvesting, chipping, and delivering chips to a pulp mill at a delivered cost that earns the developers an 8% internal rate of return on supplying bamboo chips.
2. A pulp mill investor who purchases land, constructs the pulping and bleaching systems, and delivers pulp at 50% moisture content (no capital expenditure for a pulp dryer required) to one or both nearby tissue and towel production facilities at a price that will earn a 16% internal rate of return on all revenues and cash flows.
3. One or more tissue production facilities who have determined through laboratory and pilot evaluation studies that up to 30% of their current fiber furnish can be supplied by the bamboo pulp at a price that provides a financial incentive to replace the incumbent bleached kraft market pulp.

A graphical overview of the methodology used to evaluate and compare the techno-economic feasibility of producing bamboo pulp through APMP and ABS pulping processes is presented in Fig. 1. Each step is explained in detail in the following subsections.

Targeted pulp supply scenarios

In a previous study, the Southern USA was identified as a suitable location for bamboo cultivation, providing an alternative feedstock for hygiene tissue manufacturing.[15] Specifically, South Carolina was chosen as a case study due to the presence of two nonintegrated tissue and towel mills, Anderson and Beech Island, which share proximity and currently consume significant quantities of kraft market pulp. Building upon this earlier research, this study aims to assess the feasibility of establishing three greenfield, stand-alone pulp mills (Fig. 2). These mills would produce bamboo pulp to supply 30% of the pulp demand for both the Anderson and Beech Island mills, a suitable percentage within the furnish composition that has been verified at the laboratory scale and will be published in a separate communication. One pulp mill would thus exclusively supply bamboo pulp to meet 30% of Anderson mill's market pulp demand (79 147 bone dry metric tons BDt), another solely for 30% of Beech Island mill's market pulp demand (64 035 BDt), and the third one for the combined 30% market pulp demand of both mills (143 182 BDt).[2] This study will also compare the economic impact of producing bamboo pulp using the APMP and ABS processes, leading to a final evaluation of six pulp supply scenarios.

Bamboo chips delivered cost

Bamboo *Henon* chips serve as feedstock for producing wet-lab (50% consistency) pulp at 70% ISO brightness. The delivered cost of these chips to each stand-alone pulp mill varies between USD 62-73 BDt^{-1} based on their location and pulping process (Table 1).[15] The cost of delivered feedstock is affected by the pulping process, as a lower yield process requires a larger quantity of bamboo chips for processing, ultimately resulting in higher transportation costs per bone dry metric ton of bamboo chips. The transportation cost of bamboo chips to the stand-alone pulp mills is also assumed to be paid by the plantation owner.

Technological analysis

Technology selection and configuration

Two pulping processes were selected for the technoeconomic analysis comparison: a chemical process based on ammonium bisulfite (ABS) and a mechanical process based on alkaline peroxide (APMP). The description of each process configuration is provided below. The two processes are commercially proven with wood fiber, although applications in tissue products are not widely known.[2] The concept is to install minimal capital because the pulp mill size would be significantly smaller than existing Kraft pulp mills, which required larger sizes to justify their higher capital investments. To minimize capital, it was assumed that: (1) the pulp could be produced in wet lap form at 50% moisture to avoid the high capital and energy cost of a pulp dryer; and (2) no chemical recovery process would be needed because the dissolved organic material and process chemicals

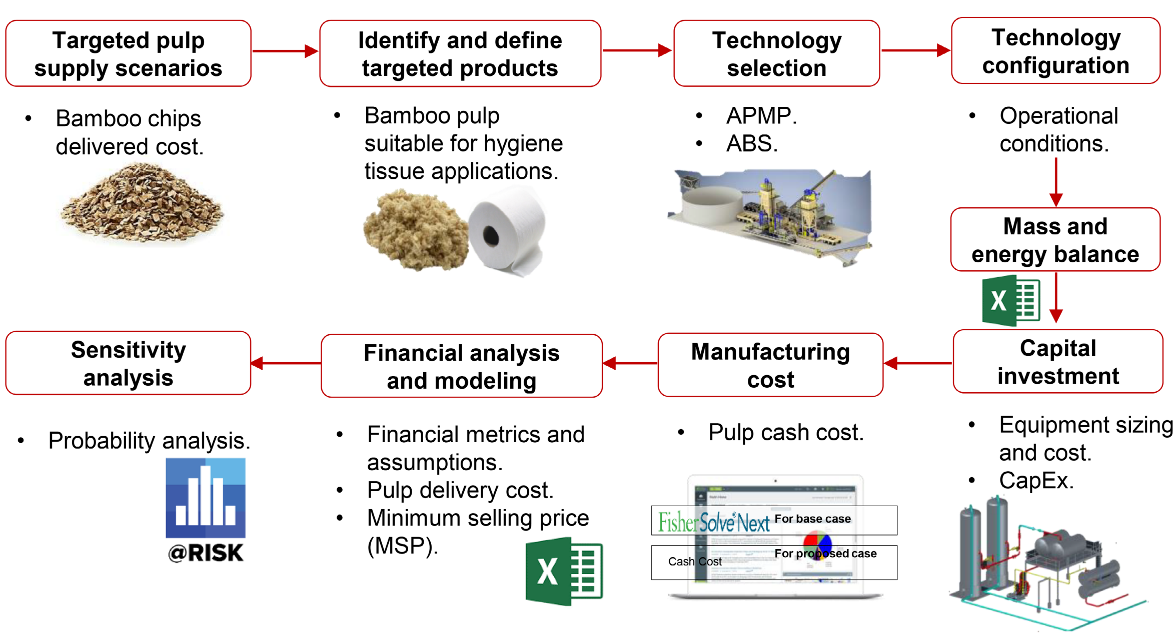

Figure 1. Graphical overview of the methodology.

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Figure 2. Graphical representation of the pulp supply scenarios evaluated.[15]

Table 1. Bamboo chips delivered cost at selected nonintegrated tissue and towel mills for APMP and ABS pulping. Adjusted from Vivas *et al.*, 2024.[15]

Nonintegrated tissue and towel mill	Pulp mill scenario	Pulping process	Feedstock delivered cost (USD BDt^{-1})
Anderson mill	A	APMP	62
Anderson mill	A	ABS	68
Beach Island mill	B	APMP	64
Beech Island mill	B	ABS	68
Both mills	C	APMP	67
Both mills	C	ABS	73

Note: Pulp mill scenario C corresponds to the simultaneous pulp supply from the Anderson and Beech Island mills. Thus, the pulp demanded and produced under scenario C is equal to the sum of the pulp demand and production in scenarios A and B.

can be disposed either as chemicals with value or treated as wastewater if no value can be found. Another option (not evaluated in this study) would be to concentrate the chemicals and ship to a nearby kraft pulp mill.

Alkaline peroxide mechanical pulping (APMP)

The APMP process integrates peroxide bleaching with alkali impregnation (e.g., NaOH, Na_2CO_3) and refining stages.[37] Initially, as exhibited in Fig. 3(a), the feedstock undergoes hot water washing to remove water-soluble contaminants before being chemically impregnated. Bamboo chips are initially impregnated with a chelating agent, diethylenetriaminepentaacetic acid (DTPA), to remove or deactivate metal contaminants and stabilize peroxide. Subsequently, they are given an alkaline peroxide (NaOH and H_2O_2) treatment to soften the lignin, facilitating fibrillation and reducing the generation of fines during subsequent refining.[44] After multiple chemical impregnation stages, the feedstock experiences two mechanical treatment stages (refining) at high consistency to separate fibers, followed by a screening stage to recycle any unseparated fibers (shives).[41] The resulting pulp is bleached and fed into a wet lap machine (a paper machine wet end and press section, but no dryers) to obtain wet lap pulp (50% consistency) suitable for shipping. All effluents from the process with high biochemical and chemical oxygen demand (BOD and COD) content (up to 25% and 30%, respectively) are collected and sent to a water treatment plant.[44] The operational conditions for process modeling are presented below.

Ammonium bisulfite chemical pulping (ABS)

Ammonium bisulfite is a variant of sulfite pulping, where the critical active species is bisulfite (HSO_3^-), formed in the presence of SO_2 and H_2O within a pH range of 2–6.[28] The process is depicted in Fig. 3(b) where a stoichiometric amount of SO_2, NH_3 and water are mixed to form ammonium bisulfite, which is then introduced into the digester as a cooking liquor. After pulping, two distinct

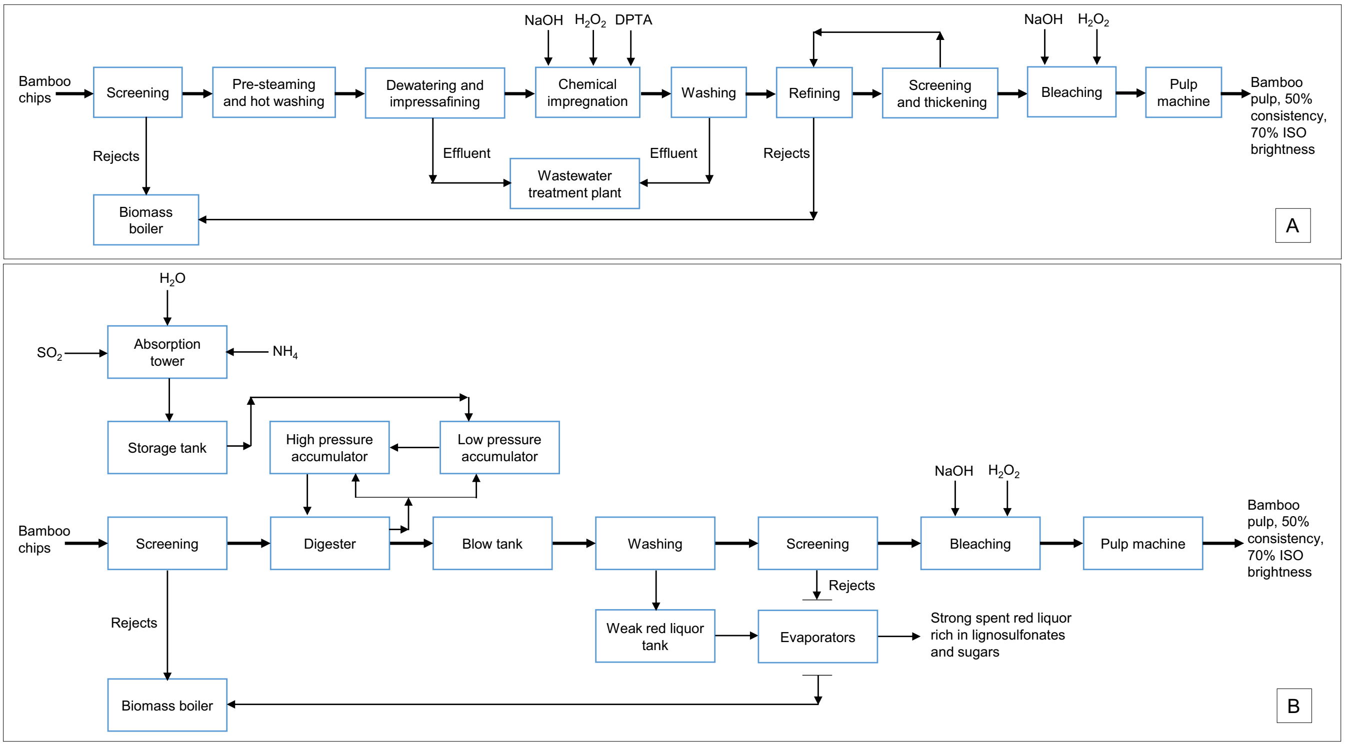

Figure 3. (a) Process flow diagram of alkaline peroxide mechanical pulping[42]; (b) Process flow of ammonium bisulfite chemical pulping.[28]

streams are generated. The first stream comprises unbleached pulp with a significantly reduced lignin content, making it suitable for subsequent peroxide bleaching process. The second stream is the spent liquor, enriched with lignin components, which is then concentrated up to 50% lignosulfonate dry solids in a six-effect evaporator. After bleaching, the pulp is fed into a wet lap machine to reduce the moisture content 50%, preparing it for shipping. The operational conditions for process modeling are presented in the next section.

Operational conditions

The process information and assumptions for the modeling and scaling up of the processes are provided in Table 2. The information was collected from experimental data, academic and industrial references targeting a bleached pulp at 70% ISO brightness for further comparison.

Mass and energy balance

The process modeling for each pulping process was conducted using Microsoft Excel spreadsheets, incorporating the detailed process information provided in the previous section. This modeling facilitated the estimation of mass and energy balances within the processes. These balances were used to determine input parameters, such as feedstock, chemicals, and energy, as well as output parameters, including products, byproducts, and effluents.

Energy balances were performed to assess the heat and electricity requirements for all energy-dependent unit operations. The heat energy consumption was quantified based on the steam required for heating the digester, evaporating water, and the bleaching process. Heating the digester involves heating the vessel and chemicals until the desired temperature is reached, while accounting for 5% of radiation losses.[45] The steam required for the six multi-effect evaporators was calculated using a steam economy factor of 5.[46] A steam requirement of 0.28 metric tons per air-dried metric ton of pulp per bleaching stage was also considered.[47] A multifuel boiler is modeled, which burns biomass rejects from the hammer mill and screening during feedstock preparation before the digester, as well as pulp rejects after pulp screening. The energy credits from burning biomass are subtracted from the total energy required for the process. The remaining energy demand is met by burning natural gas, while electricity is purchased from the grid. The boiler efficiency is 66% when burning biomass and 80% when burning natural gas.[48]

Table 2. Operational conditions for APMP and ABS pulping process simulations.[28,29,38,44,62–66]

Condition	Value
General	
Uptime (day $year^{-1}$)	350
Bamboo chips moisture content, %	15
Bamboo chips preparation (screening) yield, %	99.5
Bamboo chemical composition	
Cellulose, %	36.1
Hemicellulose, %	22.4
Lignin, %	29.3
Extractives, %	10.7
Ash, %	1.5
Alkaline peroxide mechanical pulping (APMP)	
Total pulp mill yield, % (BDt bleached pulp BDt^{-1} chips)	77
ISO brightness, %	70
Pre-steaming	
Temperature in, K	303
Temperature out, K	353
Time, s	3600
Hot washing	
Medium	Water
Retention time, s	7200
Temperature, C	363
Liquor to bamboo chips ratio (mass)	4:1
Consistency out, %	30
Dewatering	
Losses, % (based on fiber input)	0.2
Consistency out, %	30
Impressafiner	
Losses, % (based on fiber input)	0.3
Consistency out, %	60
Chemical impregnation and reaction	
NaOH charge, % mass on bamboo chips	6
H_2O_2 charge, % mass on bamboo chips	6
DPTA charge, % mass on bamboo chips	0.5
Temperature in, K	333
Temperature out, K	363
Retention time, s	7200
Liquor to bamboo chips mass ratio	4:1
Pulping yield, % (BDt pulp BDt^{-1} chips)	81
Consistency out, %	5
Refiner	
Losses, % (based on fiber input)	1
Screener	

Table 2. (Continued)

Condition	Value
Alkaline peroxide mechanical pulping (APMP)	
Consistency, %	3
Losses (rejects), % (based on fiber input)	1
Consistency rejects rate, %	4
Thickener	
Losses, % (based on fiber input)	0.01
Consistency out, %	15
Bleaching	
Bleaching yield, % (BDt bleached pulp BDt $pulp^{-1}$)	98
NaOH charge, % on bamboo pulp mass entering bleaching	1
H_2O_2 charge, % on bamboo pulp mass entering bleaching	5
Retention time, s	3600
Temperature, K	363
Consistency, %	10
Pulp wet lap machine	
Consistency after press, %	50
Ammonium bisulfite chemical pulping (ABS)	
Total pulp mill yield, % (BDt bleached pulp BDt^{-1} chips)	40
ISO brightness, %	70
Pulping	
Pulping yield, % (BDt pulp BDt^{-1} chips entering pulping)	45
Retention time, s	10 800
Initial temperature, K	343
Final temperature, K	433
Liquor to bamboo chips mass ratio (mass)	4:1
SO_2 charge, % on bamboo chips mass entering pulping	30
Free SO_2, %	0 (fully combined with NH_4)
Pressure relief, % (based on cooking liquor mass)	30
Kappa number after pulping	20
Bleaching	
Bleaching yield, %	95
NaOH charge, % on bamboo pulp mass	3
H_2O_2 charge, % on bamboo pulp mass	3
Retention time, s	3600
Temperature, K	363
Consistency, %	10
Washing	

Table 2. (Continued)

Ammonium bisulfite chemical pulping (ABS)	
Condition	Value
Dilution factor	3
Dissolved solids recovery, %	99
Consistency in, %	1
Consistency out, %	16%
Screening	
Screening losses after washing, %	3
Evaporators (6-effect)	
Steam economy, kg water vaporized kg-$^{-1}$ steam used	5
Total dissolved solids in strong red liquor, %	50
Sulfur content in strong red liquor, %	7
Pulp wet lap machine	
Consistency after press, %	50

For the ammonium bisulfite chemical pulping, the potential production of lignosulfonate was estimated, considering the remaining lignin in the strong red liquor.[28]

Economic analysis

Economic analyses for each pulp mill scenario and pulping process were performed using a cash flow analysis using Microsoft Excel. The following subsections present the details.

Material cost data

Table 3 presents the costs for all materials and utilities involved in the processes. These expenses are reported as delivered to the pulp mill gate in the reference year 2023.

Table 3. Cost data used for economic analysis.[2,67]

Costs	Value
Ammonia makeup cost, USD t^{-1}	406
SO_2 makeup cost, USD t^{-1}	308
NaOH cost, USD t^{-1}	1000
H_2O_2 cost, USD t^{-1}	880
DPTA cost, USD t^{-1}	980
Fresh water make-up* cost, USD t^{-1}	0.95
Electricity, USD MWh^{-1}	65
Natural gas cost, USD 1000*SCF^{-1}	4.73

*Water tap is considered as fresh make-up water.

Capital investment

A combined equipment list and cost references for constructing a greenfield, stand-alone pulp mill for the APMP and ABS processes are presented in Table 4. These costs are averages for North America derived industrial references. The equipment costs must be scaled up and updated using Eqn (1):

$$Equipment\ cost_1 = Bare\ equipment\ cost_0 * \left(\frac{input\ flowrate_1}{input\ flowrate_0}\right)^{SF} * \left(\frac{CEPCI_1}{CEPCI_0}\right) \quad (1)$$

where 0 and 1 represent the reference and actual values (based on pulp mill scenario), respectively.[45] Scaling factors (SF) range from 0.6 to 1 depending on equipment type,[49] and Chemical Engineering Plant Cost Index $(CEPCI)_i$ values are used to update these costs from the reference date 2011[50] to the start-up year 2023, being $CEPCI_0$ 585.7[50] and $CEPCI_1$ 803.3.[51]

After estimating the equipment cost, the fixed-capital investment is calculated by incorporating additional direct and indirect costs, as percentages of the equipment cost, along with land and infrastructure expenses.[50] Direct costs encompass elements such as equipment installation, instruments and controls, piping, electrical systems, buildings, yard improvements, and service facilities. Indirect costs, on the other hand, encompass engineering, construction expenses, legal fees, contractor fees, and contingency.[45]

Manufacturing cost and pulp cash cost

Total manufacturing cost was estimated as well as a pulp cash cost distribution to evaluate the contribution of each expense into the manufacturing and pulp cost per BDt of bamboo pulp. Pulp cash cost encompasses the direct costs associated with producing pulp at a mill, including variable costs that fluctuate directly with production volume, such as raw materials, labor, chemicals, water, energy (natural gas) and power (electricity). In contrast, manufacturing costs cover a broader range of expenses, incorporating both variable and fixed costs. These include overhead, maintenance, utilities, and depreciation.[52,53]

Financial metrics and assumptions

The main financial metrics used in this study are:

- Net present value (NPV). The sum of all present values of free cash flows over an assumed project life, using a specified discount or hurdle rate. A positive NPV signals that the project return is greater than the assumed discount rate.[54]

Table 4. Reference equipment cost list.[50,68]

Process zone	Reference input flowrate (kg h^{-1})	Bare equipment cost USD	Scaling factors
Land and infrastructure			
Land purchase	31 250	1 288 700	1.0
Land grading	31 250	175 000	1.0
Roads	31 250	1 500 000	1.0
Offices	31 250	1 130 000	1.0
Biomass handling and preparation			
Truck receiving	94 697	986 000	0.6
Raw material storage	2 000 000	2 000 000	0.6
Truck scale	94 697	110 000	0.6
Biomass cleaning	94 697	279 900	0.6
Hammer mill	8000	27 500	0.6
Biomass chopping	36 000	500 000	0.6
Transfer conveyer	94 697	5 397 000	0.6
Chemical handling and cooking liquor preparation			
Tank NH_3	1171	196 000	0.7
Tank water	451 555	250 000	0.7
Tank SO_2	410 369	236 000	0.7
Ammonium bisulfite storage tank	410 369	236 000	0.7
Absorption tower	410 369	236 000	0.7
Low pressure accumulator	410 369	236 000	0.6
High pressure accumulator	136 950	236 000	0.6
Scrubber	85 000	980 000	0.6
Pulping, washing, bleaching and pulp machine			
Batch digester	95 238	4 000 000	0.9
Blow tank	95 238	1 500 000	0.6
Blow heat condenser	95 238	500 000	0.6
Wash press feed tank/ dilution tank	1 135 500	439 000	0.5
Wash press filtrate tank	1 135 500	439 000	0.5
Screens	3583	297 297	0.6
Pre-steam bin	15 000	500 000	0.6
Feedstock washer	15 000	500 000	0.6
Dewatering screw	83 333	2 000 000	1
Impresafiner	15 000	1000,000	0.6
Impregnator	15 000	500 000	0.6
Wash press	4130	100 000	0.6
Refiners	4130	100 000	0.6
Pressure screens	1583	148 648	0.6
Thickener	26 041	912 000	0.6
Bleaching	15 000	2 000 000	0.6

Table 4. (Continued)

Process zone	Reference input flowrate (kg h^{-1})	Bare equipment cost USD	Scaling factors
Wet lap	50 000	275 000	0.6
Solid product system			
Solid product conveyer	94 697	5 397 000	0.6
Power system			
Gas-fired boiler	238 686	28 271 131	0.6
Biomass boiler	238 686	28 271 131	0.6
Water treatment			
Water plant	78 829	200 000	0.9
Waste water treatment plant	31 250	14 000 000	1
Lignosulfonate			
Weak red liquor tank	410 369	236 000	0.7
Lignosulfonate tank	410 369	236 000	0.7
Six-effect multiple effect evaporator	393 100	5 701 643	0.6

- Discount rate. The minimum rate of return that a project must surpass for it to be considered acceptable, representing investor risk-adjusted expectations.[53]
- Internal rate of return (IRR). The rate of return that makes the net present value (NPV) of an investment zero. If the IRR is greater than the hurdle rate or cost of capital, the project is considered economically viable.[55]
- Minimum required selling price (MSP). The lowest price at which a product must be sold to achieve an NPV equal to zero using a specific hurdle rate.[55]

Financial assumptions considered in this study are shown in Table 5.

Labor costs were estimated by considering the required number of employees in each pulp mill section and their wage and salary hierarchy, ranging from superintendents to operators. The number of employees for each pulp mill and pulping process scenario was derived from the authors' industrial expertise.

Pulp transportation cost

The bamboo pulp is transported to the selected nonintegrated tissue and towel mills (Anderson or/and Beech Island) and sold at the minimum required selling price (MSP) required to achieve a 16% internal rate of return (Fig. 2). To determine the MSP, the delivered cost of bamboo pulp must be considered (Table 6). These values were estimated by factoring variables such as the distance from each stand-alone pulp mill location to the chosen nonintegrated tissue and towel mills, 50% bamboo pulp moisture content, a USD 2.93 km^{-1} freight rate,[56] and a maximum truck capacity of 22 ton.[57] The delivery cost of bamboo pulp to the nonintegrated tissue and towel mills is thus covered by the pulp producer within the MSP.

Financial modeling for MSP estimation

A cash flow analysis was conducted to estimate the MSP of bamboo pulp delivered to the nonintegrated tissue and towel mill(s) to achieve the target 16% IRR. This rate is derived from the weighted average cost of capital (WACC) for the paper/forest products industry (10%), as reported by New York University (NYU) Stern School of Business,[58] with an additional 6% included as a conservative adjustment for running the models.[54,55]

The influence of lignosulfonate co-product (concentrated spent red liquor to 50% solids) price on the MSP of bamboo pulp in the ammonium bisulfite chemical pulping was also considered. The range considered for lignosulfonate prices encompassed the worst-case scenario of USD 40 t^{-1} of dry solids sold as fuel (calculated based on its heating value), a medium scenario of USD 250 t^{-1},[34] and the best-case scenario of USD 500 t^{-1}.[59] The last two lignosulfonate prices are considered to cover a range, primarily depending on the quality of the lignosulfonate obtained in the strong spent red liquor, with lignosulfonate priced at USD 500 t^{-1} being suitable for higher value applications.

Table 5. Financial assumptions considered.[2,45,53–55,69]

Financial assumptions	Values
Operation, h year^{-1}	8400
Startup year	0
Terminal year	10
Capital spending –4	0%
Capital spending –3	10%
Capital spending –2	30%
Capital spending –1	30%
Capital spending –0	30%
Annual inflation	0%
Capital investment in maintenance, % RAV	1%
Depreciation, years	10
Nominal capacity at year 1	90%
Nominal capacity at year 2	100%
Working capital, % (direct costs + revenue)	10%
Other fixed costs and overhead, % revenue	10%
Annual increase in replacement asset value, % of RAV	2%
Annual expense for operating materials, % of RAV	2%
Annual expense for other mill fixed costs	2%
Tax on profit	35%
Terminal value, multiple of EBITDA in year 15	5

Abbreviation: EBITDA, earnings before interest, taxes, depreciation and amortization; RAV, replacement asset value.

Sensitivity analysis

Sensitivity analysis assesses the impact of selected variable costs on the MSP of bamboo pulp. This analysis was performed using Microsoft Excel spreadsheets where central assumptions were varied by ±25%, and the resulting MSP values were recorded.[53,55] For the ABS sensitivity analysis, the central value for the lignosulfonate price was considered as the medium scenario at USD 250 t^{-1}. These results were then plotted to illustrate the variations.

Results and discussion

Mass and energy balance results

All inputs and outputs for each pulp mill scenario and pulping process were calculated and presented in Table 7. Concerning pulp mill scenarios, Pulp Mill A presents slightly more mass and energy requirements than Pulp Mill B, for the

Table 6. Bamboo pulp transportation cost from stand-alone pulp mills to selected nonintegrated tissue and towel mills across pulp mill scenario and pulping processes.

Nonintegrated tissue and towel mill	Pulp mill scenario	Pulping process	Distance required from stand-alone pulp mill to nonintegrated tissue and towel mills (km)	Pulp transportation cost (USD BDt^{-1})
Anderson mill	A	APMP	43	12
Anderson mill	A	ABS		
Beach Island mill	B	APMP	61	16
Beech Island mill	B	ABS		
Both mills	C	APMP	100	27
Both mills	C	ABS		

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Table 7. Inputs and outputs of each pulping process per pulp mill scenario.

Ammonium bisulfite chemical pulping (ABS)			
	Value per pulp mill scenario		
	Pulp mill A	Pulp mill B	Pulp mill C
Inputs			
Bamboo chips, BDt year^{-1}	196 768	159 199	355 967
NH_3, t year^{-1}	10 647	8614	19 261
SO_2, t year^{-1}	40 082	32 429	72 510
NaOH, t year^{-1}	2499	2022	4521
H_2O_2, t year^{-1}	2499	2022	4521
Natural gas, SCF*1000 year^{-1}	672 469	544 072	1 216 542
Fresh water, kt year^{-1}	1261	772	2033
Electricity, MWh year^{-1}	52 131	42 177	94 308
Outputs			
Bamboo bleached pulp, BDt year^{-1}	79 147	64 035	143 182
Lignosulfonate solids, t dry year^{-1}	67 541	54 645	122 187
Alkaline peroxide mechanical pulping (APMP)			
	Value per pulp mill scenario		
	Pulp mill A	Pulp mill B	Pulp mill C
Inputs			
Bamboo chips, BDt year^{-1}	102 766	83 144	185 910
NaOH, t year^{-1}	6912	5592	12 504
H_2O_2, t year^{-1}	10 143	8206	18 349
Natural gas, SCF*1000 year^{-1}	232 560	188 156	420 716
Fresh water, kt year^{-1}	1597	1291	2888
Electricity, MWh year^{-1}	57 067	46 171	103 238
Outputs			
Bamboo bleached pulp, BDt year^{-1}	79 147	64 035	143 182

Note: Pulp Mill A is located and scaled to supply the Anderson Mill, Pulp Mill B is similarly located and sized to supply the Beech Island Mill, while Pulp Mill C represents the case of a single pulp mill optimally located to supply pulp to both mills.

same pulping process selected, whereas in Pulp Mill C the requirements are double. In terms of bamboo chip demand, ABS requires more raw material due to its lower pulping yield of 45%, compared to APMP with a pulping yield of 81%. Despite ABS being chemical-intensive and having higher natural gas consumption, it is notable that APMP has higher consumption of NaOH and H_2O_2, as well as electricity and fresh water.

Capital investment

Capital investments and their breakdown are estimated for each pulp mill scenario and pulping process, as depicted in Fig. 4(a). The color segments in Fig. 4(a) represent the capital investment required for each pulp mill section (from biomass to lignosulfonate/wastewater treatment plant), direct costs (from purchased equipment installation to service facilities) are blue-colored, whereas indirect costs (from engineering to contingency), and land costs are green labeled. By comparing pulping processes, it is evident that APMP requires a slightly lower capital investment (USD 75 million to 133 million) than ABS (USD 86 million to 141 million). The major cost contributors to the capital investment for both processes are the pulping, washing, and bleaching sections. The wastewater treatment plant is the next cost contributor for APMP, while the biomass and power sections are for ABS. The APMP mills face challenges in handling waste liquor (effluent), which involves significant environmental and financial burdens related to chemical losses and the capital investment required for wastewater treatment plants to comply with effluent discharge regulations.[60]

The following takeaways can be observed when comparing capital investment requirements for the two evaluated processes. First, in the biomass handling section, ABS necessitates around 40% more investment than APMP. This is primarily a result of the lower yield (45%) of the ABS process, requiring a larger amount of feedstock to be processed to obtain equal bamboo pulp quantities in comparison with APMP, with a yield of 81%. Second, the chemical section's investment is higher for ABS due to the involvement of more chemicals, demanding proper handling and storage. Third, the power section is driven by steam production to meet heat requirements in the system, with ABS requiring a higher investment compared to APMP, as expected based on the previous section. Although APMP is electricity intensive, it is assumed that it is supplied from the grid in all pulp mill scenarios. Fourth, the capital investment for the lignosulfonate section in the ABS process is primarily driven by the investment in the six-effect evaporator, which concentrates spent liquor to achieve a 50% lignosulfonate solids content.

In all the pulp mill scenarios and pulping processes that were evaluated, direct costs represented between 60 and 70% of the fixed-capital investment. For each pulping process, it is important to highlight that as the targeted production increases, the capital investment also increases, transitioning from Pulp Mill B with lower pulp production (64 035 BDt year^{-1}) to Pulp Mill C with higher pulp production (143 182 BDt year^{-1}). However, when the capital expenditure per

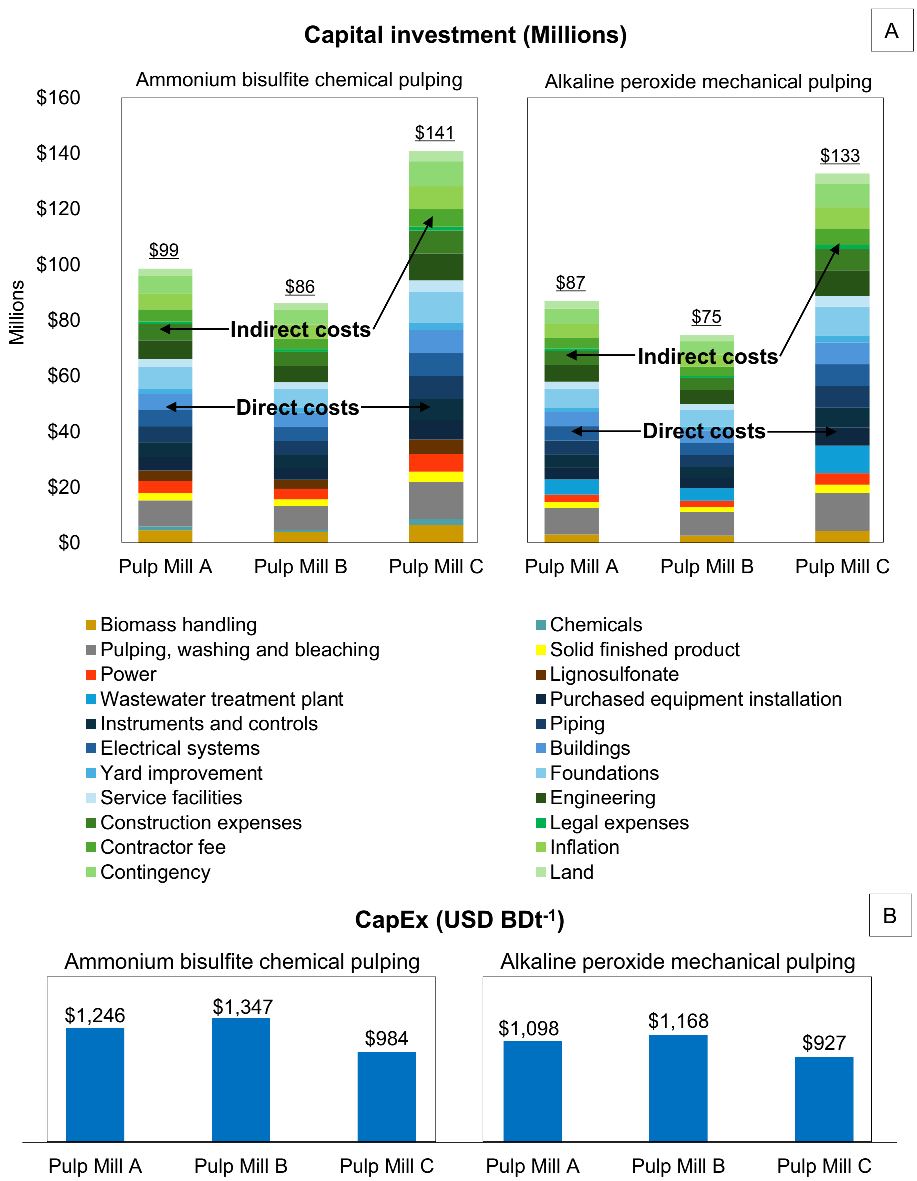

Figure 4. (a) Capital investment and (b) CapEx comparison between pulp mill scenarios and pulping processes.

unit of bamboo pulp produced (CapEx) is estimated in each scenario (Fig. 4(b)), the economy of scale allows for the lowest CapEx in Pulp Mill C and the highest at Pulp Mill B.

Pulp manufacturing cost and cash cost

Manufacturing costs, pulp cash costs, and their breakdown are calculated for each pulp mill scenario and pulping process, as illustrated in Fig. 5, based on the first year of total production capacity after startup (year 2). Manufacturing costs vary from USD 783 to 867 BDt^{-1} for ABS and from USD 600 to 685 BDt^{-1} for APMP. The most significant cost contributors depend on the pulping process. Chemicals, bamboo cost, and depreciation are the primary cost contributors for ABS. In contrast, for APMP, the leading cost contributors include chemicals, depreciation, and, with an equal impact, energy, and bamboo cost.

Analyzing each cost contributor, ABS has higher bamboo and chemical costs, which, as mentioned previously, is due to lower yield (higher bamboo chips requirements) and more chemicals involved, respectively. Bamboo cost represents the cost of bamboo chips delivered to the stand-alone pulp mill required to produce 1 metric ton of pulp, considering pulping yield and losses. Energy costs are similar for both processes as shown in Fig. 5(a). However, if the direct pulp cash cost breakdown is examined in Fig. 5(b), specifically into electricity

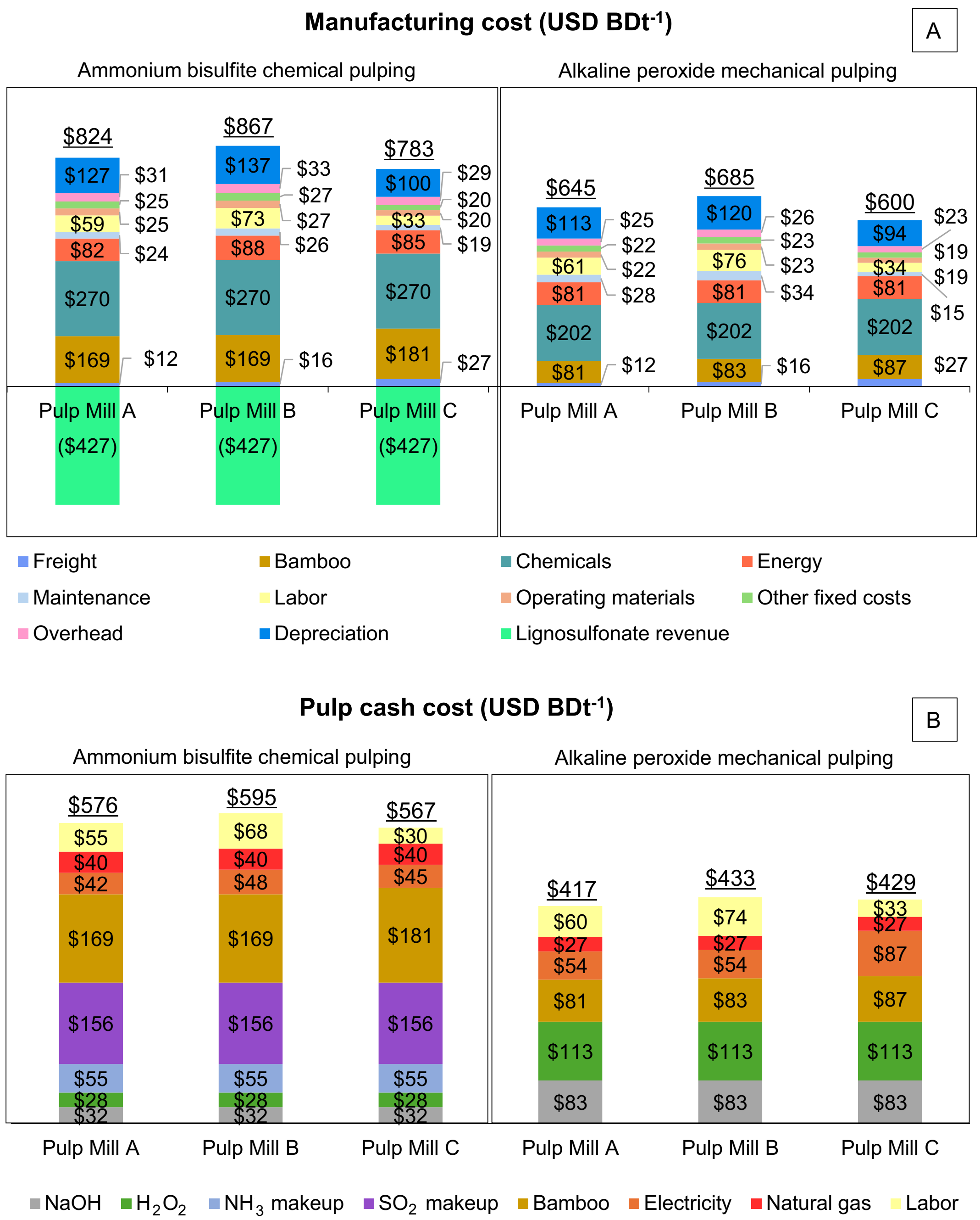

Figure 5. (a) Manufacturing cost and (b) Pulp cash cost comparison between pulp mill scenarios and pulping processes.

and natural gas costs, as mentioned previously, ABS requires higher natural gas consumption, while APMP requires higher electricity consumption. Even though each pulping process has different pulp sections and requires different quantities of personnel, the labor cost involved for ABS and APMP results in similar values. Furthermore, depreciation costs were estimated to illustrate the impact of capital expenditure on manufacturing costs. As expected, due to the values explained in the previous section, ABS has a higher depreciation cost than APMP, and within the pulping process, the pulp mill scenario with higher pulp production (Pulp Mill C) has a lower depreciation cost than the one with lower pulp production (Pulp Mill B). Finally, the freight cost represents the delivery of the bamboo pulp produced from a stand-alone pulp mill (Pulp Mill A, B or C) to the nonintegrated tissue and towel mills (Anderson and Beech Island). Therefore, as the evaluated pulp mill scenarios for ABS and APMP are the same, this results in equal freight costs.

Minimum required selling price

The MSPs of bamboo pulp across various pulp mill scenarios and pulping processes are estimated and presented in Fig. 6. These prices are calculated to ensure that pulp mill investors achieve an internal rate of return of 16%. Figure 6(a) illustrates that the MSP for ABS ranges from USD 544 to USD 686 BDt^{-1} of pulp, while APMP ranges from USD 766 to USD 899 BDt^{-1}. For both pulping processes, the minimum required selling price decreases as pulp production increases, with the lowest MSP for Pulp Mill C and the highest for Pulp Mill B.

This comparison reveals that bamboo pulp produced by ABS results in a lower MSP, even though this process incurs higher capital investment and manufacturing costs. This is attributed to the revenue generated by producing and selling lignosulfonate at USD 500 t^{-1} (dry equivalent), with 50% solids content and 7% sulfur content. However, evaluating the impact of the lignosulfonate price on the ABS MSP was crucial. To that end, three possible lignosulfonate prices were considered: USD 40, 250, and 500 t^{-1}, representing scenarios from lignosulfonate solids being suitable for fuel to high-value applications. The results depicted in Fig. 6(b) indicate that the lignosulfonate price has a significant inverse effect on MSP; as the lignosulfonate price increases, MSP decreases. However, even when considering the worst case scenario of a lignosulfonate price of USD 40 t^{-1} as fuel, the resulting MSPs ranges between USD 920 and 1078 BDt^{-1}, which are comparable with prices reported for bleached eucalyptus kraft (BEK) market pulp ranging from USD 756 to 1106 BDt^{-1} (USD 680 to 995 $ADST^{-1}$).[2,61] The medium price generates an MSP that can compete with BEK market pulp and is close to the MSP obtained by the APMP process. On the other hand, the USD 500 t^{-1} lignosulfonate price scenario generates the lowest minimum required selling price; this scenario is likely to occur as lignosulfonates have a well-established market. However, a deep characterization analysis of these lignosulfonates will provide a better understanding of potential applications and determine its price.

Sensitivity analysis

The sensitivity analysis aimed to identify cost variables with a significant influence on MSP. Variations in CapEx, bamboo cost, chemicals, electricity, natural gas, and labor, as well as lignosulfonate price were considered. Figure 7 illustrates the resulting MSPs for Pulp Mill C scenario. The ABS MSP ranges from USD 688 to 827 BDt^{-1}, and APMP MSP ranges from USD 700 to 831 BDt^{-1} of bamboo pulp. In APMP

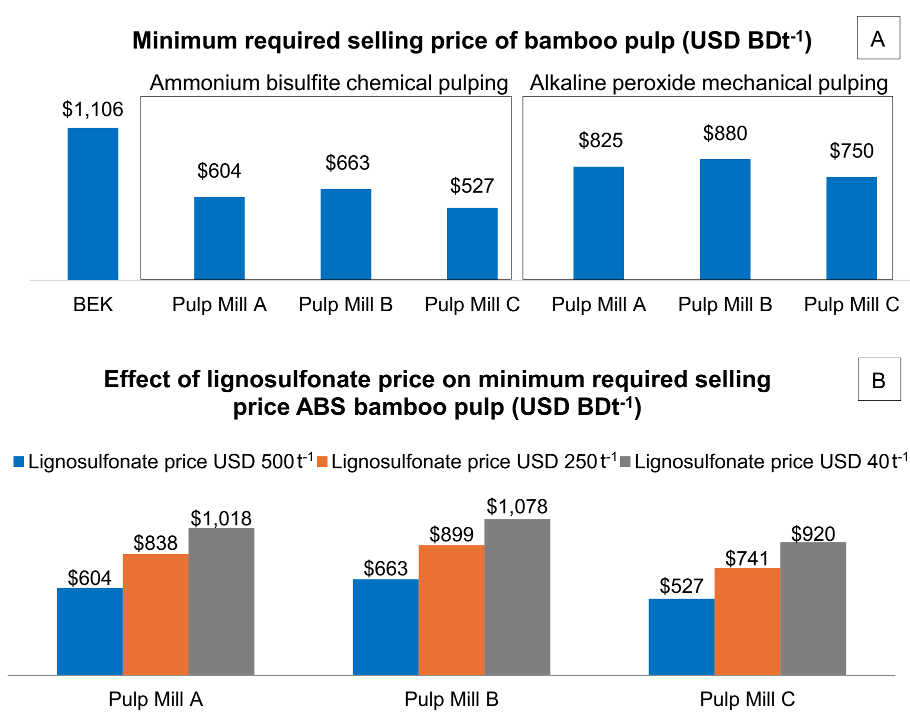

Figure 6. (a) Minimum required selling price (MSP) comparison between pulp mill scenarios and pulping processes; (b) ammonium bisulfite chemical pulping MSP comparison between lignosulfonate prices and pulp mill scenarios.

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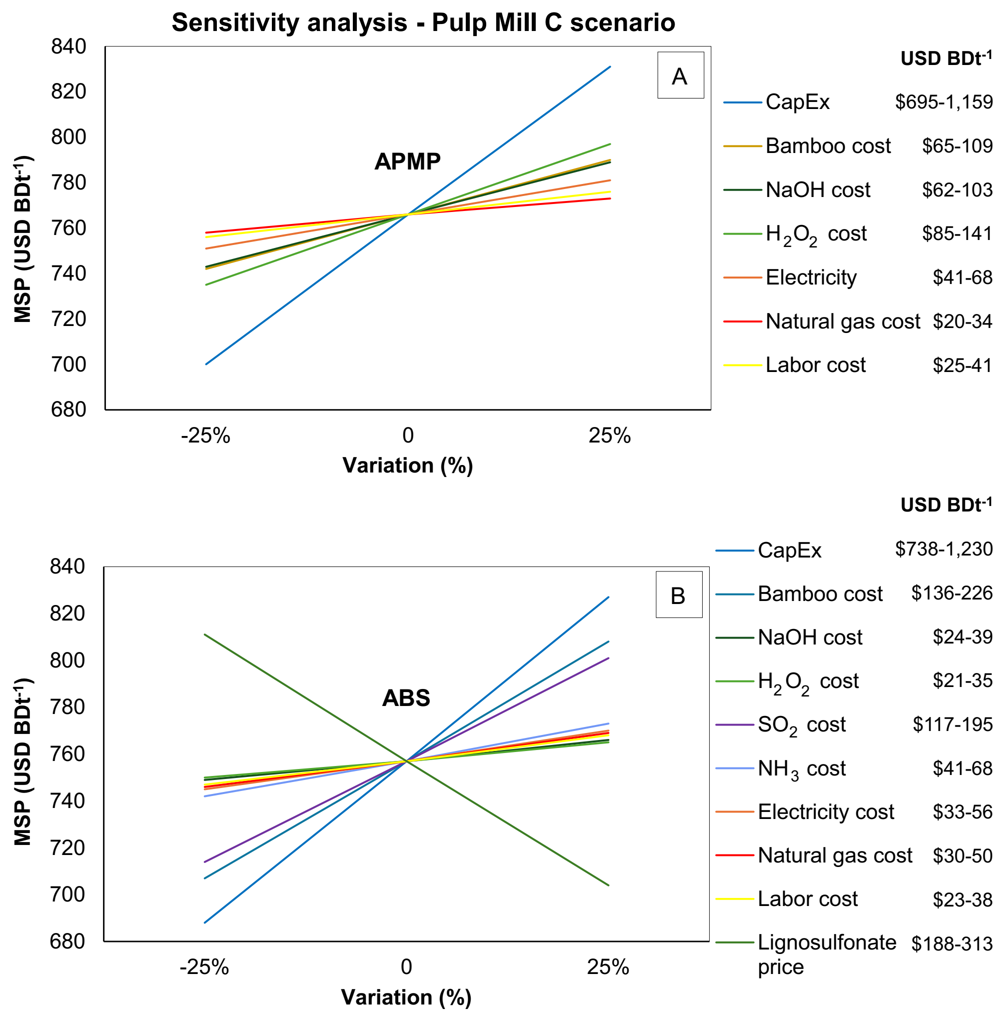

Figure 7. Sensitivity analysis of selected cost contributors for the (a) Alkaline peroxide mechanical pulping (APMP) and (b) Ammonium bisulfite chemical pulping (ABS).

(Fig. 7(a)), CapEx is the most impactful variable, followed by H_2O_2, bamboo, and NaOH costs, all with proportional effects. As these factors increase, the APMP MSP also increases. In contrast, for ABS (Fig. 7(b)), the major contributors are CapEx, followed by lignosulfonate price (with an inverse effect), bamboo and SO_2 cost with proportional effect. The variation in the price of lignosulfonate in ABS results in an impact of around −7% on MSP. Although ABS and APMP share bamboo cost and CapEx costs as significant contributors, it is important to note that the impact of bamboo cost variations on ABS MSP is higher, around 6%, compared to APMP, which experiences about 3% variation. In contrast, for CapEx variation, both ABS and APMP exhibit similar variations: 9% and 8%, respectively. These results offer valuable insights for decision-makers, providing an assessment of the project's financial feasibility and low-risk exposure under the Pulp Mill C scenario.

Final comments and future perspective

The findings of this study can be applied to other fiber-based applications, particularly those that use very expensive hardwood market pulp. For example, folding carton applications, where lower brightness is required, mean lower chemical charges, higher yields, and even better profitability, considering that fiber, especially yield, and chemical costs play an essential role in the MSP. Based on the analysis, it can be inferred that producing bamboo fibers in the Southern USA can be a viable and cost-effective opportunity for hygiene tissue. This will benefit businesses and reduce the dependence of the USA on China's bamboo pulp supply. It will also lead to lower CO_2 emissions of bamboo consumer goods in the USA market, where more environmentally friendly energy sources are used, and less transportation is required. Future research will evaluate the carbon footprint of producing bamboo fibers locally and compare them with imported and other domestically produced fibers for USA hygiene tissue.

Conclusions

This study assessed the feasibility of producing bamboo fibers for hygiene tissue in South Carolina, USA. It explored supplying wet-lap, 70% ISO brightness bamboo pulp to nonintegrated tissue and towel mills using three pulp mill scenarios and APMP and ABS pulping processes. Ammonium bisulfite chemical pulping (ABS) requires higher capital investment (USD 86 million to 141 million) and manufacturing costs (USD 783 million to 867 million BDt^{-1}) compared to alkaline peroxide mechanical pulping (APMP) (USD 75 million to 133 million, USD 600 to 685 BDt^{-1}). However, ABS generates additional revenue from spent liquor sales with 50% lignosulfonate solids, which results in a lower MSP of USD 544 to 686 BDt^{-1}. Based on end application suitability, the variation in lignosulfonate price from USD 40 to 500 t^{-1} inversely impacts the MSP, ranging from USD 1078 to 544 BDt^{-1}, respectively. Capex, bamboo cost, and chemical cost (H_2O_2 for APMP, SO_2 for ABS) are primary factors contributing to bamboo pulp MSPs. Due to the economy of scale, lower bamboo pulp MSPs resulted in Pulp Mill C scenario, producing 143 182 BDt (the highest pulp production) to supply Anderson and Beech Island mills simultaneously. Although ABS generates lower MSPs, both ABS and APMP can be competitive against kraft market pulps.

As the price fluctuations of lignosulfonate significantly impact MSPs for ABS, further analysis is required to establish a final price. Despite being sold for fuel at USD 40 t^{-1}, the resulting MSP is still lower than the reported price for kraft market pulps. Conversely, APMP economics could be comparable to or better than ABS if located near a wastewater treatment plant, reducing capital investment and MSPs. These findings underscore the importance of considering various factors in determining the economic viability of bamboo pulp production for hygiene tissue, opening the door for further exploration and decision-making in this field.

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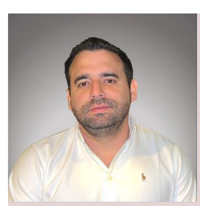

Alonzo Pifano

Alonzo Pifano, a chemical engineer and PhD candidate at North Carolina State University, USA, researches the use of nonwood fibers in tissue paper production, focusing on the cost effectiveness of substituting bleached kraft hardwood pulps with nonwood fibers in hygiene products.

Ramon E. Vera

Ramon E. Vera, a chemical engineer from the University of Los Andes, Venezuela with a PhD in forest biomaterials from North Carolina State University, USA, leads nonwood pulping research and develops competitive and cost-effective nonwood pulping processes for alternative fibers in paper, textiles, and nonwovens.

Fernando Urdaneta

Fernando Urdaneta is a chemical engineer from the University of Zulia, Venezuela. He is currently pursuing a PhD at North Carolina State University, USA. His research focuses on converting nonwood feedstock for tissue paper applications while actively developing sustainable solutions for tissue paper technologies.

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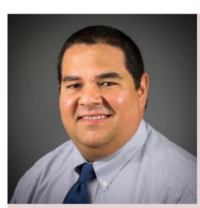

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