Evaluating Chemical-, Mechanical-, and Bio-Pulping Processes and Their Sustainability Characterization Using Life-Cycle Assessment

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Pulp and paper manufacturing constitutes one of the largest industry segments in the United States in term of water and energy usage and total discharges to the environment. More than many other industries, however, this industry plays an important role in sustainable development because its chief raw material—wood fiber—is renewable. This industry provides an example of how a resource can be managed to provide a sustained supply to meet society's current and future needs. The objective of this work is to present streamlined environmental life-cycle assessments (LCA) between chemical (kraft–sulfate), mechanical (or thermomechanical), and biopulping processes. This LCA would help us to evaluate the industry's current experience and practices in terms of environmental stewardship, regulatory and nonregulatory forces, life cycles of its processes and products, and future developments.

The pulping industry has been traditionally using mechanical or chemical pulping methods, or a combination of the two, to produce pulps of desired characteristics. Mechanical pulping accounts for about 25% of the wood pulp production in the world today. Mechanical pulping, with its high yield, is viewed as a way to extend the forest resources. However, mechanical pulping is electrical energy–intensive and yields paper with less strength compared to that produced by the chemical pulping process. These disadvantages limit the use of mechanical pulps in many grades of paper. Chemical pulping accounts for about 75% of the wood pulp production in the world. This process produces paper with very high strength. However, the process has the disadvantages of being capital- and energy-intensive, giving relatively low yields, producing troublesome waste products, and producing by-products that are of relatively low values. Environ Prog, 23: 347–357, 2004

Keywords: *life-cycle assessment (LCA), chemical pulping, mechanical pulping, biopulping, sustainability, TRACI*

INTRODUCTION

A new technology that offers a biopulping process with the potential to ameliorate some of these problems is being tested on a commercial scale. Biopulping treats wood chips with a natural wood-decaying fungus before mechanical pulping and can save substantial amounts of electricity, significantly reduce the amount of air pollutants (including CO_2 and some odor-causing

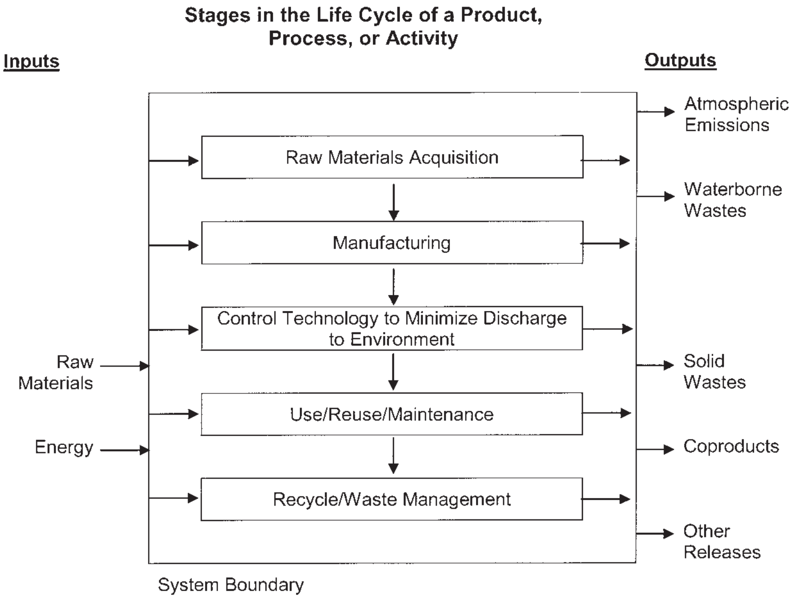

Figure 1. Life-cycle assessment stages and boundaries [1].

total reduced sulfur compounds) and water pollutants (BOD, COD, TSS) compared with conventional pulping, improve paper quality, and enhance economic competitiveness.

The USEPA's TRACI model was used to assess the chemical, environmental, and human health impacts attributed to three pulp and papermaking processes. The results obtained from the biopulping process indicate a significant reduction in environmental and human health impacts. The biopulping process proves to be more sustainable in terms of economic advantage, and environmental and human health benefits.

LIFE-CYCLE ASSESSMENT

Life-cycle assessment or analysis (LCA) is a tool for evaluating the environmental performance of a process, product, or activity, starting from raw material extraction, through manufacture, to use and final disposal. This is known as a "cradle-to-grave" approach (Figure 1). This approach enables identification of the major environmental impacts throughout the life cycle of a product, process, or activity, and the assessment of the possibilities for effecting improvements [1].

LCA was first defined in the way we know it today at the Vermont Conference of the Society of Environmental Toxicology and Chemistry [2]. The concept is holistic, promoting analysis, quantification, and understanding of all the environmental impacts associated with an activity. The provision of such information aids decision making and helps in the formulation of environmental strategy and policy; as such, LCA has been accepted into the mainstream of environmental thought and management [3].

The LCA methodology constitutes four main stages: goal definition and scoping, inventory analysis, impact assessment, and improvement assessment. Goal definition and scoping define the purpose of the study, the system to be studied, the functional unit, and issues relating to data quality. The functional unit forms the basis on which systems can be compared as it relates to the service(s) provided by the process, product, or activity under analysis. Inventory analysis quantifies the environmental burdens (i.e., material and energy use, emissions, and solid wastes) associated with the provision of the functional unit. Impact assessment aims to assess the environmental impacts of the burdens identified in the inventory analysis, providing manageable and meaningful data. Improvement assessment identifies and evaluates options for reducing the environmental impacts of the system under study.

Other applications are related to identifying possibilities for improvements in the environmental performance of an existing process or product or for the design of new ones. These studies are usually industry-specific and are mainly used for product or process innovation as well as for demonstrating the environmental progress of a company. Another use of LCA is for public policy making by governments [4, 5].

APPLICATIONS OF LCA

Because of its holistic approach to system analysis, LCA is becoming an increasingly important decision-making tool in environmental system management. Its main advantage over other, site-specific, methods for environmental analysis, such as environmental impact assessment or environmental audit, lies in broadening the system boundaries to include all burdens and impacts in the life cycle of a product or a process, and not focusing solely on the emissions and wastes generated by the plant or manufacturing site.

As an environmental management tool, LCA has two main objectives. Its first objective is to quantify and evaluate the environmental performance of a process or a product and so help decision makers choose be-

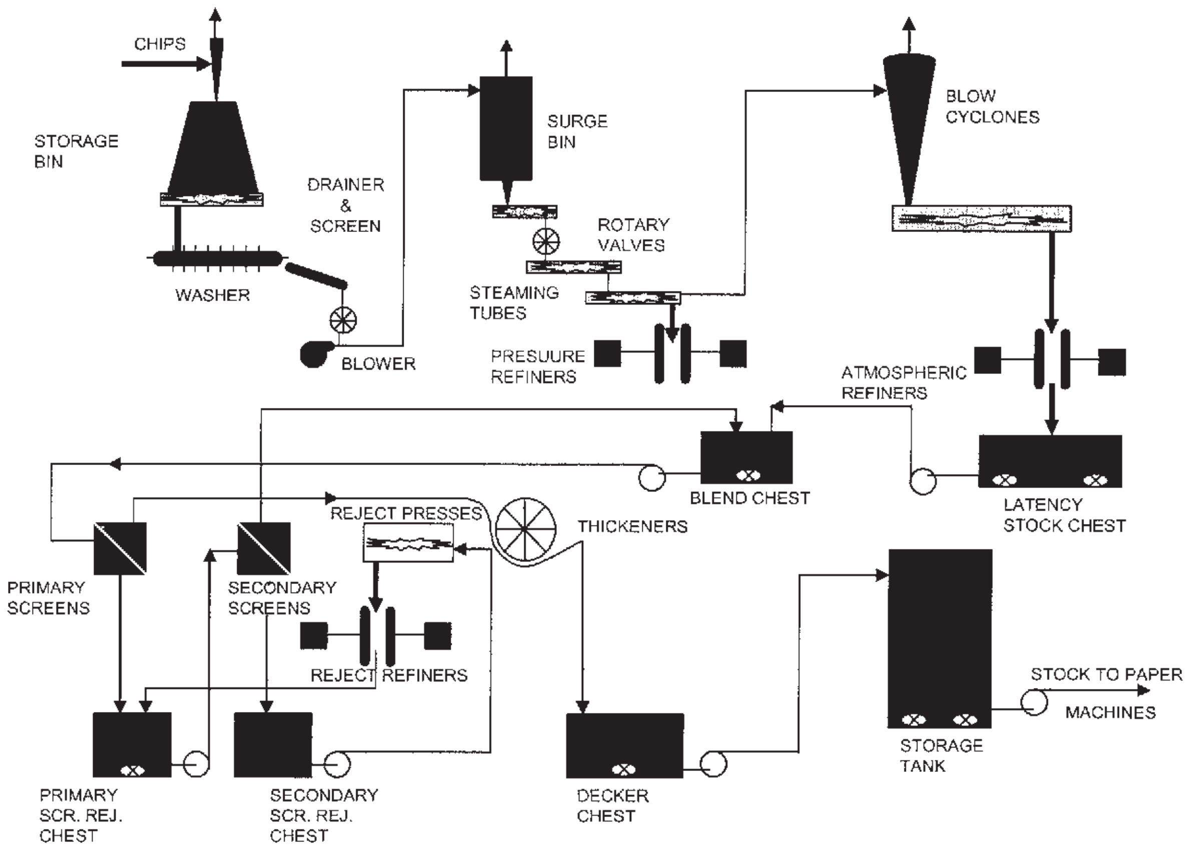

Figure 2. Basic flow diagram for TMP process [8].

tween alternative products or processes. Another objective of LCA is to provide a basis for assessing potential improvements of the environmental performance of an existing or newly designed system. This can be of particular importance to engineers and environmental managers because it can advise them on how to modify or design a system to decrease its overall environmental impact.

LCA can thus be used both internally by a company or externally by industry, policy makers, planners, educators, and other stakeholders. If the results of LCA are to be used internally by a company, then possible areas where LCA can be useful include, but are not limited to, the following:

- strategic planning or environmental strategy development
- problem solving in the system
- environmental reporting, auditing, and marketing
- identification of opportunities for, and tracking of, environmental improvements
- process and product design, innovation, improvement, and optimization

External applications of LCAs include uses of LCA as a marketing tool, to support environmental labeling or claims, or informational purposes, or to support policy decisions. LCA, green chemistry, green engineering, design-for-environment, industrial ecology, and other emerging areas of chemical engineering and environmental engineering provide greater opportunities for developing sustainable and innovative processes and products [6].

In this work, we focus only on LCA related to three processes: chemical-, mechanical-, and biopulping using wood chips. This streamlined LCA approach will help to identify which process is more sustainable by considering environmental impacts, human health and safety, and process economics.

THE PULPING PROCESSES

Mechanical Pulping

Mechanical pulping, as the name implies, relies on mechanical energy to convert wood to pulp. Current mechanical pulp manufacturing processes constitute several high-energy grinding and refining systems, including refiner mechanical pulping (RMP) process, the thermomechanical pulping (TMP) process, the chemimechanical pulping (CMP) process, and the chemithermomechanical pulping (CTMP) process [7, 8]. Mechanical pulping accounts for about 25% of the wood pulp production in the world today. Mechanical pulping, with its high yield, is viewed as a way to extend these resources. However, mechanical pulping is electrical energy-intensive and yields paper with lower strength compared with that produced by chemical pulping.

Figure 2 shows the basic flow diagram for TMP [8]. Thermomechanical pulping is a modification of RMP; it

Table 1. Make-up chemical, and energy, water, and land use per 1000 ton oven dry pulp and paper production using chemical-, mechanical-, and bio-pulping.

Component	Chemical (kraft/sulfite)	Mechanical	Bio-TMP
H_2O_2	0.5%	2.0%	2.5%
Na_2O–SiO_2	—	2.0%	2.5%
$MgSO_4$	0.5%	0.5%	0.5%
NaOH	3.0%	1.0%	1.5%
$NaSO_4$	2.5%	—	—
O_2	4.8%	—	—
CIO_2	3.0%	—	—
H_2SO_4	1.0%	—	—
Corn steep liquor	—	—	0.5%
Energy use* (MJ/1000 ton/day O.D. pulp)	3.15×10^7	8.24×10^7	5.25×10^7
Water use (gal/1000 ton/gay O.D. pulp)	1.6×10^7	6.0×10^6	6.0×10^6
Land use (acre/1000 ton/day O.D. pulp)	20	20	25

* Derived from Table 2.

involves steaming the raw material for a short period of time before and during several refining stages. The steaming serves to soften the chips, with the result that the pulp produced has a greater percentage of long fibers and less shives than RPM. Most often, heating and refining are both done under pressure (TMP), but some systems refine under atmospheric pressure. Chemicals are sometime added at the various stages of refining. In the TMP process, the chips are usually steamed under a pressure of 20–40 psi for 2 to 4 min before refining.

Table 1 presents an average quantity (in %) of make-up chemicals that are typically needed for mechanical/thermomechanical pulping [9]. Table 2 presents the energy consumption in various operations of TMP and papermaking process [10]. Table 3 shows a range of effluent loads and other environmental impacts of the TMP process [11, 12]. The data from Tables 1, 2, and 3 are used to quantify the environmental and human health impacts that will be discussed later in the quantitative analysis section.

A study by the National Council of the Paper Industry for Air and Stream Improvement [13] on estimating volatile organic compounds (VOCs) are likely to be released along with the steam during the cooking and refining process. The range of VOC emissions can vary between 1.0 to 7.0 pounds of carbon per ton of pulp, depending on the wood species. No emissions other than VOC are expected from the mechanical pulping process.

Chemical Pulping Processes

The following discussion centers on chemical pulping processes, which supply more than two thirds of world's wood pulp. The most widely used chemical pulping process in papermaking is the kraft, or sulfate, process. Other chemical-pulping process (mainly using acid sulfite and soda) are sometimes combined with various chemical-recovery subprocesses. First used over a century ago, these processes now result in recovery of 90% of the inorganics, which are used in the pulping process. Nearly 100% of the dissolved organics are converted to energy. The typical kraft process involves turning logs into wood chips, which are then pulped (Figure 3) [7]. The major steps in chemical pulp and papermaking processes include wood yard operations, pulping, deknotting, washing and screening, chemical recovery, pulp bleaching, pulp drying, and paper making [7, 8]. Various gaseous, particulate, liquid, and solid waste streams are produced within a kraft mill (BOD, COD, TSS, NO_x, SO_2, CO, CO_2, PM, TRS, odor, and ash). A wealth of information in the existing literature addresses various treatment methods and pollution prevention and process optimization techniques for these waste streams. Some of the pollution-prevention advancements and a summary of reduction in total environmental discharges (wastewater, air emissions, and solid and hazardous wastes) from kraft and sulfite mills across the United States over the last 20–25 years are discussed in the literature cited in the reference section [14, 15].

Table 1 presents an average quantity (in %) of make-up chemicals that are typically needed for chemical pulping [9]. Chemical pulping uses 63% more chemical than mechanical pulping, and 53% more than biopulping. Table 2 presents the energy consumption in various operations of chemical pulping and papermaking processes [10]. Table 3 shows a range of effluent loads and other environmental impacts of chemical pulping and papermaking processes [12]. The data from Tables 1, 2, and 3 are used to quantify the environmental and human health impacts that will be discussed later in the quantitative analysis section.

Biopulping: A Review of a Pilot-Plant Project

Biopulping is the treatment of wood chips and other lignocellulosic materials with lignin-degrading fungi before pulping. Ten years of industry-sponsored research has demonstrated the technical feasibility of the technology for mechanical pulping at a laboratory

Table 2. Summary of specific energy consumption in current pulp and papermaking processes (million Btu/ton pulp unless specified otherwise).

Process	Range of energy variation		Typical average
	Minimum	Maximum	
Wood preparation component*			
Debarking	0.16	0.25	0.19
Chipping	0.27	0.38	0.32
Pulping component: Chemical pulping			
Digesting	1.5	8.00	4.7
Washing	0.32	1.10	0.57
Refining/screening	2.0	4.20	3.0
Drying	4.0	5.00	4.2
Mechanical pulping			
Stone grinding/refining	13.2	15.20	14.5
Mechanical refining			18.6
Thermomechanical refining	19.6	23.10	19.7
Wastepaper pulping	4.0	5.82	4.3
Bio-TMP pulping	13.72	16.17	13.8
Bleaching component	1.2	14.20	7.5
Chemical recovery component			
Evaporation/concentration	2.05	5.35	4.4
Recovery furnace auxiliary	2.00	4.00	2.64
Recausticizing	1.00	1.05	1.02
Lime kiln	0.94	2.50	2.0
Kraft recovered energy**	−4.00	−20.0	−15.0
Papermaking component*			
Stock preparation	2.7	5.01	3.38
Sheet formation	0.13	0.40	0.26
Pressing			0.32
Drying	5.0	20.00	7.40
Auxiliary component*			
Lighting and space heating	0.42	2.00	1.68
Power plant	1.00	1.50	1.25

* Million Btu/ton of paper.
**Energy recovered as steam from kraft recovery boiler.

scale. Two 50-ton outdoor chip pile trials conducted at the USDA Forest Service, Forest Products Laboratory (FPL) in Madison, WI have established the engineering and economical feasibility of the technology. After refining the control and the fungus-treated chips through a thermomechanical pulp (TMP) mill, the resulting pulps were made into papers on the pilot-scale paper machine at FPL. In addition to the 30% savings in electrical energy consumption during refining, improvements in the strength of the resulting paper were seen as a result of fungal pretreatment. Because of the stronger paper, we were able to substitute at least 5% kraft pulp in a blend of mechanical and kraft pulps. This recent work has clearly demonstrated that economic benefits can be achieved with biopulping technology through both the energy savings and substitution of the stronger biopulped TMP for more expensive kraft, while maintaining the paper quality.

Introduction to Biopulping

Biopulping, which uses natural wood decay organisms, has the potential to overcome these problems. Fungi alter the lignin in the wood cell walls, which has the effect of "softening" the chips. This substantially reduces the electrical energy needed for mechanical pulping and leads to improvements in the paper strength properties. The fungal pretreatment is a natural process; therefore, no adverse environmental consequences are foreseen [16–18]. Based on the results of previous work and discussions with mill personnel, we envision a fungal treatment system that fits into existing mill operations with minimal disturbance. Figure 4 is a conceptual overview of the biotreatment process in relation to existing wood yard operations. Wood is harvested and transported to the mill site for debarking, chipping, and screening. Chips are decontaminated by steaming, maintaining a high temperature for a sufficient time to decontaminate the wood chip surfaces,

Table 3. Effluent loads from the manufacture of forest products.

Product	Effluent (m^3/metric ton)	Suspended solids (kg/metric ton)	BOD (kg/metric ton)	COD (kg/metric ton)	N (g/metric ton)	P (g/metric ton)
Pulp						
Sulfate pulp, unbleached	20–60	12–15	5–10	20–30	200–400	80
Sulfate pulp, conventional bleaching*	60–100	12–18	18–25	60–120	300–500	120
Sulfate pulp, ECF or TCF**	30–50	10–15	14–18	25–40	400–600	100
Sulfite pulp, conventional bleaching	150–200	20–40	30–40	60–100	100–200	60
Groundwood, unbleached	6–10	10–30	10–15	30–50	100–200	50
TMP, unbleached	6–15	10–30	15–25	40–80	100–200	70
TMP, peroxide bleached	6–5	10–30	20–40	60–100	200–300	100
Recycled fiber, deinked	10–20	5–10	20–40	40–80	100–200	40
Paper and paperboard						
Fine paper, coated	30–50	10–20	3–8	10–20	50–100	5
Newsprint	10–25	5–10	1–3	2–4	10–20	5
Folding boxboard	10–25	5–10	2–4	3–6	50–100	8
Sack paper	15–30	5–10	2–4	4–8	100–200	15
Tissue	20–40	5–10	1–3	3–6	50–80	8

Note: The figures in the table were compiled from measurements made at Finish mills. ECF, elemental chlorine free; TCF, total chlorine free.
* Kappa number 20–30, depending on wood species.
**Extended cooking, oxygen delignification, kappa number 8–14, depending on wood species.

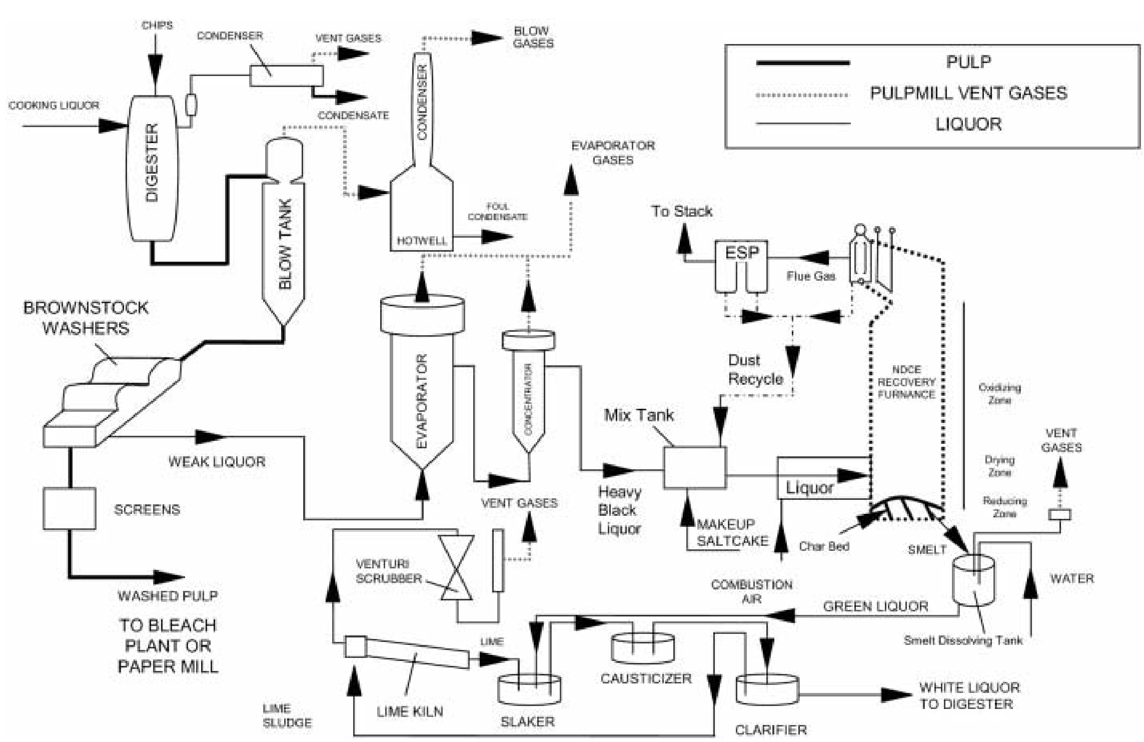

Figure 3. Schematic diagram of a typical kraft sulfate pulping and recovery process [7].

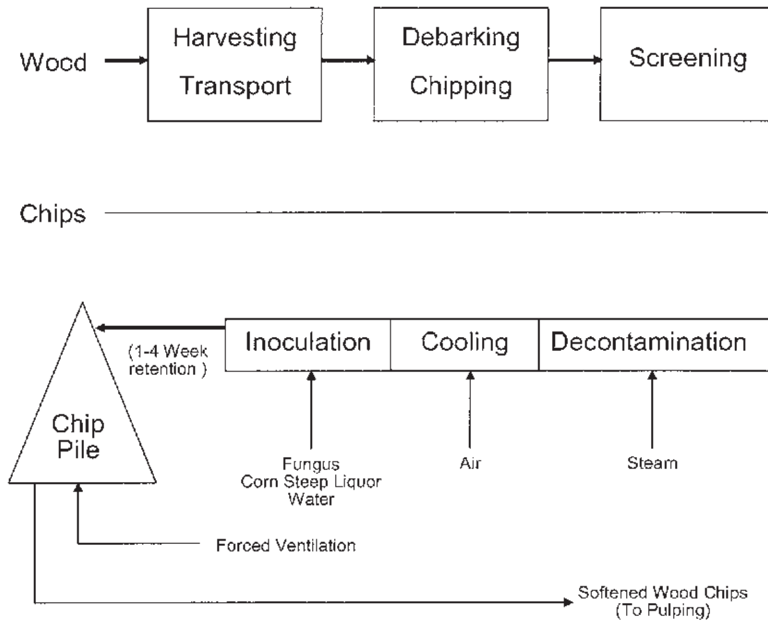

Figure 4. Overview of the bio-pulping process.

and then cooled so that the fungus can be applied. The chips are then placed in piles that can be ventilated to maintain the proper temperature, humidity, and moisture content for fungal growth and subsequent biopulping. The retention time in the pile is 1 to 4 weeks. Recent efforts have focused on bringing the successful laboratory-scale procedures up to the industrial level. Our laboratory process treats approximately 1.5 kg of chips (dry weight basis) at one time. In our scale-up experiments that took biopulping from this lab scale to larger scales, certain implementations of each step were chosen. The chosen implementation allowed us to reach our two goals for this phase of the project: (1) To demonstrate that chips can be decontaminated and inoculated in a continuous process rather than as a batch process; and (2) to demonstrate that the process scaled as expected from an engineering standpoint. The following discusses the results obtained during the scale-up trials in relation to industrial processes.

In reactor scale-up studies, Kirk and others [16] investigated two types of reactor systems: tubular reactors and chip piles. The tubular reactors have an advantage in obtaining the necessary engineering and kinetic data for scaling-up the process. The one-dimensional nature of the system is easy to analyze and model. The reactor also allows for well-controlled air flow in the system with air flow patterns that are well known. Heat loss from the system is easily controlled with exterior insulation, thus achieving conditions that would be experienced in the center of large chip piles. Details on the configurations of these reactors and the chip piles have been published [16].

Table 1 presents an average quantity (in %) of make-up chemicals that are typically needed for biopulping. The biopulping process requires 6.5% inorganic chemicals, and 0.5% organic corn steep liquor (25% solid and 75% water) is used to provide a nitrogen source for fungus [9]. Chemical pulping, on the other hand, requires 53% more chemicals than biopulping. Table 2 presents the energy consumption in various operations of biopulping and papermaking processes [10]. Table 3 shows a range of effluent loads and other environmental impacts of biopulping and papermaking processes [9, 12]. The data from Tables 1, 2, and 3 are used to quantify the environmental and human health impacts that will be discussed later in quantitative analysis section.

Economics and Environmental Benefits of the Biopulping Process

The economic benefits of biopulping, evaluated based on the process studies and engineering data, result from several effects. Energy reduction at the refiner was used as the primary criterion for the effectiveness of biopulping. For a 2-week process, the savings should be a minimum of 25% under the worst-case conditions of wood species and minimal process control, whereas up to nearly 40% can be achieved under some circumstances. Additionally, mills that are currently throughput-limited as a result of refiner capacity may achieve total capacity increases as a result of biopulping. The improved strength of the biomechanical pulps would allow the required strength of the blend to be achieved with a lower percentage of the kraft pulp in those cases where the pulps are blended. Finally, only benign materials are used, and no additional waste streams are generated. An economic analysis of the process yielded very favorable results. The analysis of a 200 ton/day TMP mill are summarized here [19]. Under different scenarios and assumptions for utility costs, equipment needs, and operating costs, the net savings can range from \$10 to more than \$26 per ton of pulp produced, with an estimated capital investment of $2.5 million. Mills that are refiner-limited can experience throughput increases of over 30% from the reduction in refining energy by running the refiners to a constant total power load. Even a modest throughput increase of 10%, coupled with the energy savings of 30%, results in a payback in less than 1 year. This is equivalent to a savings of $34 per ton at a 15% rate of return on capital. Furthermore, many mills blend mechanical pulps and kraft pulps to achieve the optical and strength properties desired. Additional benefits of over $10 per ton can be realized when the anticipated stronger biopulped TMP is partially substituted for kraft at a 5% rate. The results of a 600 ton/day analysis have also been published [20]. This preliminary analysis is subject to appropriate qualifications. The capital costs are subject to some variability, in particular the costs associated with integrating the new facility into an existing site. The additional advantages of biopulping, including the environmental benefits and pitch reduction, have not been quantified in this report. Finally, much of this analysis is site-specific, depending on the operating conditions at the particular mill considering incorporating biopulping into its operations.

Although the environmental benefits of biopulping for mechanical pulping have not been quantitatively determined in an economic sense, we can discuss the benefits qualitatively. Sykes [18] determined that there were no environmental problems with the effluent from a biopulping process. In terms of greenhouse gases, there is a net benefit to the biopulping process. The process itself is oxidative, producing carbon dioxide as the fungus metabolizes the various wood components. However, based on the typical generation efficiency of electrical energy, the reduced energy requirements (approximately 30%) significantly lower the overall generation of carbon dioxide when the entire system is analyzed. Finally, in terms of biological issues with using fungi in the wood yard, there are benefits to using the biopulping fungus. The biopulping fungus outcompetes the normal cohort of fungi and other organisms that will grow in an uncontrolled wood chip pile. Some of these other organisms, such as *Aspergillis*, can be detrimental to human health. The biopulping fungi are naturally occurring in the forests of the world and have no known health effects on humans.

QUANTITATIVE ANALYSES USING THE USEPA MODEL: TRACI

The tool for the reduction and assessment of chemical and other environmental impacts (TRACI) is described along with its history, the research and methodologies it incorporates, and the insights it provides within individual impact categories.

TRACI, a stand-alone computer program developed by the U.S. Environmental Protection Agency (USEPA), facilitates the characterization of environmental stressors that have potential effects, including ozone depletion, global warming, acidification, eutrophication, tropospheric ozone (smog) formation, ecotoxicity, human health criteria–related effects, human health cancer effects, human health noncancer effects, fossil fuel depletion, and land-use effects. TRACI was originally designed for use with life-cycle assessment (LCA), but it is expected to find wider application in the future [21–24].

The categories of odor, noise, radiation, waste heat, and accidents are outside of the U.S. EPA's purview and are usually not included within case studies in the United States for various reasons, including, perhaps, because the perceived threat from these categories is often considered minimal, local, or difficult to predict. The resource depletion categories are recognized as being of significance in the United States, especially for fossil fuel, land, and water use.

For the development of TRACI, each of the above impact categories was considered and its current state of development and perceived societal value were assessed. The traditional pollution categories of ozone depletion, global warming, human toxicology, ecotoxicology, smog formation, acidification, and eutrophication were included within TRACI because various programs and regulations within the U.S. EPA recognize the value of minimizing effects from these categories. The category of human health was further subdivided into cancer, noncancer, and criteria pollutants (with an initial focus on particulates) to better reflect the focus of

Table 4. Emissions from chemical-, mechanical-, and bio-pulping and papermaking processes, 1000 ton O.D. per day.

Pollutant	Chemical	Mechanical	Bio (TMP)
Acetone, lb	1.5×10^3	—	—
BOD, lb	4.4×10^3	1.76×10^3	1.76×10^3
CO_2,* lb	3.5×10^6	8.0×10^6	5.5×10^6
CO, lb	5.5×10^4	5.5×10^3	5.5×10^3
Chloroform, lb	8.5×10^2	7.5×10^2	7.5×10^2
COD, lb	6.0×10^3	1.0×10^3	5.0×10^2
Ethanol, lb	5.0×10^2	5.0×10^1	—
H_2S, lb	2.35×10^3	—	—
Isoprene, lb	1.0×10^3	1.0×10^3	1.0×10^3
Methane, lb	8.2×10^3	2.7×10^3	2.7×10^3
Methanol, lb	2.3×10^3	6.0×10^2	6.0×10^2
Nitrogen, lb	7.5×10^2	—	—
NO_2, lb	3.5×10^4	1.0×10^3	5.0×10^2
NO, lb	3.5×10^4	1.0×10^3	5.0×10^2
SO_2, lb	1.75×10^4	—	—

* CO_2 emissions would depend on actual nonrenewable and renewable fuels, and purchased electricity used. Emissions from wastewater treatment plant and other biological processes are not included. In Washington State, 60% energy used in the pulp and paper mills are generated from renewable sources (almost all from hydro), and 40% from purchased electricity generated from natural gas, coal, and oil. The CO_2 emissions from renewable energy sources assumed zero. Typical values of 70% combustion efficiency and 60% electricity transmission efficiency were assumed. For an overall efficiency factor of 42% in calculating CO_2 emissions from non-renewable sources power generating plants to pulp mills was used.

Table 5. Environmental and human health impacts characterization results in % for chemical-, mechanical-, and bio-pulping processes using TRACI.

Impacts %	Chemical	Mechanical (TMP)	Bio-pulping (TMP)
Global warming	21	47	32
Photochemical smog	44	28	28
Acidification	97	2	1
Ecotoxicity	36	32	32
Human health cancer	36	32	32
Human health noncancer	36	32	32

U.S. EPA regulations and to allow methodology development consistent with U.S. regulations, handbooks, and guidelines [25, 26]. Smog-formation effects were kept independent and not further aggregated with other human health impacts because environmental effects related to smog formation would have become masked and/or lost in the process of aggregation. Criteria pollutants were maintained as a separate human health impact category, allowing a modeling approach that can take advantage of the extensive epidemiological data associated with these well-studied impacts.

MODEL INPUT AND OUTPUT

It is important to note that data quality is fundamental to LCA and its interpretation. Some of the data quality issues such as reliability and consistency can be overcome by using standardized database, which are starting to emerge after years of data compilation and their incorporation into publicly and commercially available databases.

Table 4 presents some chemical release data that are used in TRACI. Table 5 presents the overall environmental and human health impacts, including global

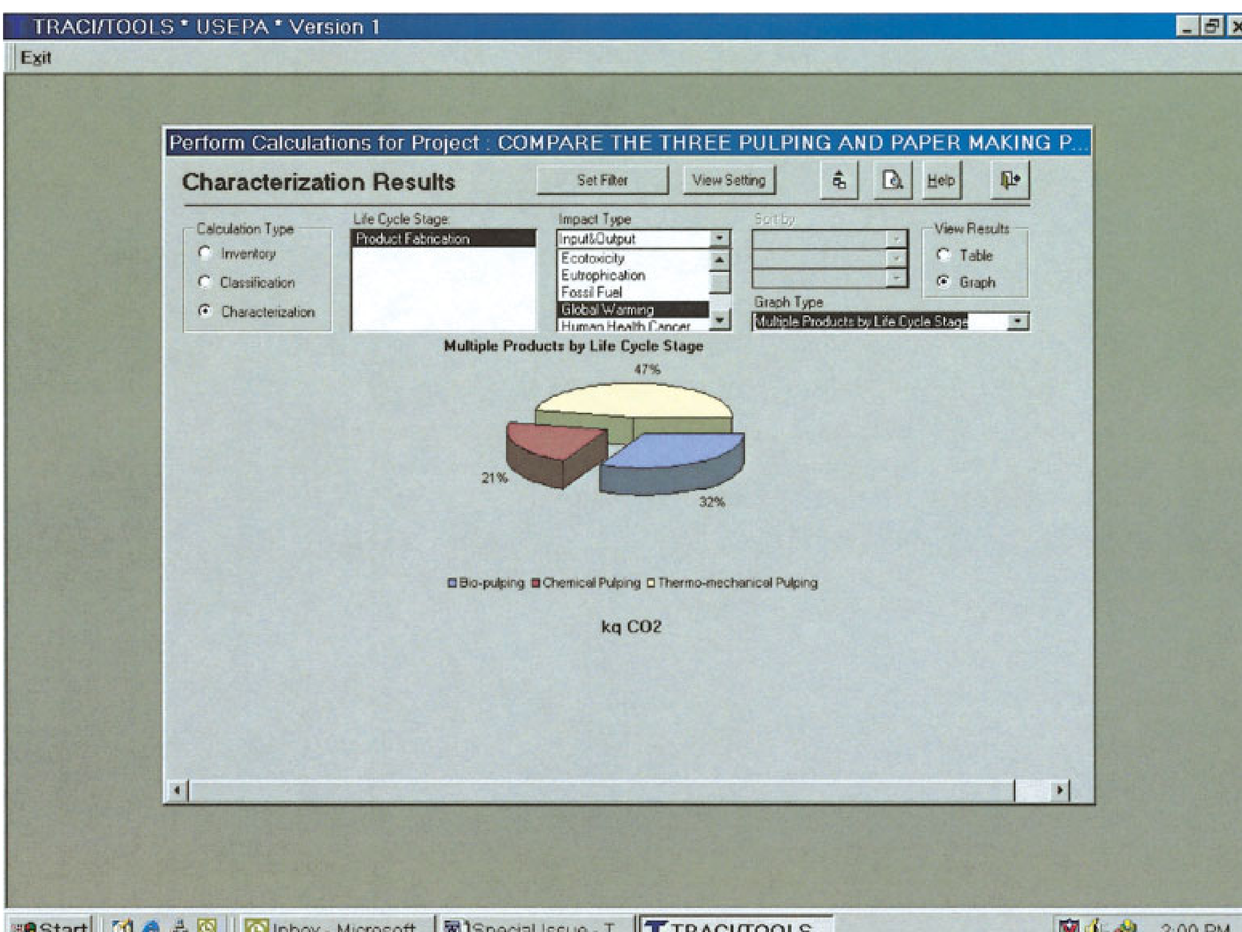

Figure 5. TRACI's global warming characterization for chemical-, mechanical-, and bio-pulping. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

warming, smog formation, human health criteria pollutants, acidification, eutrophication, and ecotoxicity. The results indicate that biopulping has a lower environmental impact than that of the TMP process because of its reduced energy consumption. Biopulping also has a lower impact than that of chemical pulping in all the measures except global warming. One should note that the total CO_2 production per ton was the highest for chemical pulping, but because kraft recovery furnaces are fired with lignin derived from the wood, a renewable resource, this contribution to greenhouse gases was assumed to be net zero. Figure 5 shows global warming characterization results predicted by TRACI.

These results likely indicate that biopulping is the preferred process when the electrical supply is dominated by renewable energy sources. In cases where the fuel mix for producing electricity is largely fossil fuels, chemical pulping provides a process powered by renewable energy but at a cost of higher hazardous waste emissions.

CONCLUSION

This streamlined LCA clearly indicates that biopulping in the papermaking process has several advantages over chemical and mechanical processes as follows:

- Reduced electrical energy consumption (at least 30%) over mechanical pulping
- Potential 30% increase in mill throughput for mechanical pulping
- Improve paper strength properties
- The TRACI model indicates a significant reduction in environmental and human health impacts
- The biopulping process proves to be more sustainable in terms of not only economic advantage but also environmental and human health benefits.

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