Cellulose pulp extraction from vegetable wastes: considerations about environmental and economic sustainability criteria

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Abstract

The improvement in current processes and in new processes triggers the search for materials and practices that can enable such advancement. However, in order to suit these improvements, it is relevant to consider sustainable issues. This paper presents sustainable approaches for processes and product development. From these approaches it was possible to derive guidelines that may be used as criteria for the analysis of pulp extraction processes, with focus on their environmental and economic features. Therefore, the assessment regarding these criteria use was done from the analysis of industrial processes of pulp extraction through bibliographic research and through opinion of experts from this field. The analysis of industrial processes of pulp extraction has shown practices developed in this sector, vis-à-vis sustainable requirements and the trends for processes improvement in order to make them more sustainable.

Keywords: Sustainability; sustainable approaches; pulp extraction processes; cellulose pulp; environmental impacts assessment.

1 Introduction

Currently companies that seek after innovations or improvements in product or process development with an emphasis on sustainability, meet up with requirements of technical, economic and also environmental natures. Concepts for reducing negative environmental impacts, combined with economic gains, have emerged as premises for starting up projects related to product and process development. So, it is appropriate to consider the term eco-efficiency, which combines economic benefits with the more efficient use of resources and the prevention of emissions, based on the idea of "producing more with less" (WBCSD, 1998). In the pursuit of eco-efficiency, managers need support, whether in the form of guidelines, tools, methods or strategies, in order to transform their production processes.

There are many approaches dealing with sustainability that mention both the economic aspects and the negative environmental impact associated with production processes or product development. The more comprehensive approaches take into account the production chain of the business and its effects on society, while other approaches are limited to the operations within a chain, sector or specific process (MANZINI and VEZZOLI, 2002). According to the authors the application of an environmentally-conscious strategy from the beginning stages of a project makes it possible to limit problems and thereby prevent loss of resources in repairing already caused environmental damage. They also mention that, in general, it is unlikely that one single strategy will be the best for meeting all environmental requirements and, for this reason, suggest a combination of environmental practices and strategies to achieve improvement objectives. So it is recommended to study different sustainability approaches, as ZERI Method (Zero Emissions Research & Initiatives) (PAULI, 1996; PAULI, 1998), Cradle to Cradle (McDONOUGH and BRAUNGART, 2002), Clean Production (GREENPEACE, 1997; THORPE, 1999; CLEAN PRODUCTION ACTION, 2010), Green Engineering (ANASTAS and ZIMMERMAN, 2003), Green Chemistry (ANASTAS and WARNER, 1998), Cleaner Production (CP) (CNTL, 2003), Design for Environment (DfE) or Ecodesign (FIKSEL, 1996; LUTTROPP AND LAGERSTEDT, 2006; VEZZOLI and MANZINI, 2008; BACK et al., 2008) and Green Supply Chain (EPA, 2000; SRIVASTARA, 2007). Approaches that extend beyond the horizons of a factory are

strategic in nature, since they present a systemic view of the business, and their applications entail multiple efforts.

The pulp and paper industry, which in Brazil is very important in environmental, economic and social terms, serves as a case for evaluating sustainability (LINS and OUCHI, 2007). In light of the direct environmental impact it has, due to greenhouse gas emissions, waste generation and effluent disposal, regulatory agencies in the country impose strict environmental requirements on companies in the sector. Therefore, the sector is striving to review processes for the purpose of saving and reusing water, energy conservation, adopting alternative sources of raw materials and reducing the consumption of material resources (LINS and OUCHI, 2007; SOUZA et al., 2008; LINS and ZYLBERSTAJN, 2010). The process conditions and raw materials used are factors that influence the sector's performance, since the chemical processes for cellulose pulp extraction are the largest source of environmental impact in the pulp and paper industry (EPA, 2010). So, the choice of raw materials, which can stem from the waste of another process, the reuse of energy and materials, are elements that can contribute to economic and environmental gains.

Knowledge and understanding of the chemical processes for cellulose extraction which use lignocellulosic materials, as well as the identification of guidelines for minimizing adverse environmental impact and obtaining economic gains are needed in order to analyze processes. From these guidelines, the possibility is then examined of designing an industrial cellulose extraction process that is more efficient from an environmental and economical point of view, contemplating the use of lignocellulosic plant waste, instead of wood. Enhanced sustainability is then achieved incrementally, on the basis of tests and the adaptation of existing extractive processes for application in different lignocellulosic plant materials. Considering the information presented, the research question is: is it possible to select a current pulp extraction process to be adapted to cellulose extraction from plant waste raw materials, while attending sustainable principles as well? The goal of this study is to select a chemical process for cellulose extraction that is flexible enough for use with lignocellulosic plant waste, based on the determination of economic and environmental criteria. These criteria were developed according to the guidelines contained in the approaches that deal with sustainability in production processes. This research focus is not the proposition of an innovative industrial extraction process. It is limited to the analysis of the transformation stage of raw materials until the pulp is obtained (pulping), the analysis of waste and emissions that are generated and set ups in the case of discontinuous processes. The analysis will be performed according to compliance or non-compliance with the criteria of interest. In this study, the aspect of economic gains takes into account the possibility of reusing resources and energy within the process, in addition to the efficient use of these resources with the least waste possible, thereby avoiding the accumulation of waste for further treatment.

2 Theoretical review

This section presents the cellulose extraction processes and approaches that deal with sustainability.

2.1 Industrial cellulose extraction processes

Cellulose is the most commonly found carbohydrate in plants. However, its source is lignocellulosic materials, in which other compounds are also present, such as hemicellulose, lignin, extractives and inorganic compounds (D'ALMEIDA, 1988). The pulping process aims to remove the lignin to get a pulp with high fiber content. The evolution of technologies applicable to different chemical processes enables adjustments of process variables that lead to process optimization, that bring benefits in economic and environmental terms. Most of the pollutants emitted by industrial operations in the manufacturing of pulp and paper occur in the pulping and bleaching stages, where various chemical components are used. The bleaching operation is not within the scope of this study.

2.1.1 Acid processes

The sulfite pulping process is based on the use of acid solutions with sulfite (SO_3^{2-}) or bisulfite (HSO_3^-) ions, which characterize the aqueous solution with free sulfur dioxide (SO_2) and sulfur dioxide in combination. In the aqueous solution it is added an alkaline solution such as (Ca $(OH)_2$), NaOH, NH4OH and (Mg $(OH)_2$) although the most commercially applied alkaline solution is (Mg $(OH)_2$), once it has a facilitated recovery system, both for energy and chemical reagents.

The advantages of using the sulfite process are based in the highly sensitive to types of raw material. It is worth noting that a limited number of species of wood can be used, such as hardwoods that have low resin content and high density. Most softwood, with the exception of pine, is considered less susceptible to acid pulping (SIXTA, 2006). Also this process produces a clear pulp that is easier to bleach and can be refined more quickly and with less expenditure of mechanical energy. However, the major disadvantages of the process are that it cannot be applied to any and all plant species, requires longer cooking times and generates a less resistant paste due to increased cellulose degradation (SIXTA, 2006; EPA, 2010).

2.1.2 Alkaline processes

There are two main alkaline pulping processes, which are soda process and sulfate or kraft process. In both processes, sodium hydroxide (NaOH) is the main reagent in the cooking liquor, but sodium sulfide (Na_2S) is also present in the sulfate process only, in an approximate proportion of 75% Na_2S and 25% NaOH. The use of the kraft process has been more widespread than the soda process due to the economic benefits in being able to recover the chemical agents, thereby avoiding their release into the environment, in addition to improved yield and pulp quality (pulp produced by percentage of raw material) (EPA, 2010). The kraft process is selective and flexible, since it can be adapted to many distinct types of raw materials, besides enabling the recovery of chemical reagents for the formation of the cooking liquor and power generation (EPA, 2010). However, the soda process is recommended in cellulose production based on straw, bagasse and other agricultural waste. The selectivity of kraft process over soda process is greater, that is, it has a greater ability to remove lignin without a prolonged attack on the carbohydrate fraction of the wood (SMOOK, 1994). The disadvantage of using sodium sulfide (Na_2S) in the kraft liquor is the release of malodorous and toxic organic compounds, such as methyl mercaptan (CH_3SH), dimethyl sulfide (CH_3SCH_3), dimethyl disulfide (CH_3SSCH_3) and other reduced sulfur compounds, referred to as total reduced sulfur (TRS), which are formed during the delignification (D'ALMEIDA, 1988; SIXTA, 2006). Such compounds are strictly controlled in pulp industries, since they have to meet environmental requirements (SIXTA, 2006).

The main reasons that lead to improvements and modifications in the kraft process are environmental in nature: to reduce sulfur compound emissions or obtain pulps with a higher delignification content that requires a smaller chemical load for bleaching. Alkaline processes allow the use of chemical additives, since the use of additives can lead to environmental and economic benefits. These modifications are being studied, in light of the behavior of the variables, the reagents used and way the kraft process is conducted. The use of additives which enhance the efficiency of pulping reactions, enabling the alkaline load and sulfur compounds to be reduced and resulting in less malodorous pollution, is an alternative that has great application potential and has subsequently been developed by companies. The use of anthraquinone ($C_{14}H_8O_2$) as an additive in the two main alkaline processes affects the delignification reactions by promoting a higher delignification rate and less carbohydrate degradation, thus counteracting some of the main mechanisms responsible for low alkaline pulping yield (SIXTA, 2006). Nevertheless, the results show that the effect of anthraquinone is more notable in soda pulping as compared to kraft pulping (HOLTON, 1977).

2.2 Approaches that address sustainability

Even when considering one single company or sector, every product creation stage have impacts on the environment, besides the products themselves. These stages need to be studied from the very beginning, starting with product design, since each stage has the potential for environmental improvement, including

the choice of raw materials, technologies and processes involving manufacturing and product waste recovery, as presented in some approaches in the sequence.

2.2.1 Green supply chain

Vachon and Klassen (2006) define the green supply chain as the interaction between organizations, within the production chain, in relation to prevention of pollution at the source, which may occur upstream, in negotiations with suppliers, or downstream, in the contact with consumers. This approach deals with integrating the environment and management of the supply chain, for activities related to product design, definition and selection of raw material sources, final product delivery to consumers and end-of-life product management after its use (SRIVASTARA, 2007). This type of interaction helps generate significant results for improving environmental and economic performance throughout the chain (EPA, 2000; VACHON and KLASSEN, 2006).

2.2.2 Cradle to Cradle

This approach deals with technological metabolism, where the waste from one process should serve as raw material for another, as in a cycle of nature (PAULI, 1998; McDONOUGH and BRAUNGART, 2002). It is like the ZERI method, which is a systemic approach, proposed by Pauli (1996). It states that in designing products and developing production systems, waste from one activity should be considered as raw material for another. Its goal is zero emissions in systems, based on designs with an emphasis on the life cycle, economic and ecological strategies (PAULI, 1996; PAULI, 1998; GUIMARÃES, 2006).

The approach, which also acts as a certification of materials and practices related to their use, entails generating products from "cradle to cradle", as opposed to the concept of "cradle to grave". Cradle to Cradle is highly complex, because it restricts the use of products that can cause any harm to the environment, and thus also promotes the certification of the system's elements (materials, reuse of materials, energy, water and social responsibility) (MBDC, 2007). Cradle to Cradle certification seeks to develop designs that add more value to the environment during and after the use of materials, as opposed to elaborating plans to minimize environmental impact (McDONOUGH and BRAUNGART, 2002).

2.2.3 Green chemistry

Green chemistry (GC) refers to the use of a set of 12 principles to reduce or eliminate the use and generation of hazardous substances in designing chemical products and processes. Professionals in the chemical industry are constantly striving to develop efficient processes and methods, since efficiency is important for both measuring the quality of the transformation process of a raw material and analyzing its technical and economic feasibility. Economic considerations play a key role in process design, since the selection of raw materials is based on greater availability and lower cost (ANASTAS and WARNER, 1998). Some of the principles are similar to those from Green Engineering (ANASTAS AND ZIMMERMAN, 2003) and includes: opt to prevent waste generation, as opposed to treating it once it has been created in order to eliminate its toxic properties; design synthetic methods to maximize the incorporation of all the substances used throughout the process into the final product; to use and produce substances that are non-toxic (or slightly toxic) to human health and the ecosystem; design chemicals at the molecular level so as to achieve the desired functions and minimize their toxicity. For more details see Anastas and Warner (1998). The guidelines set forth by the authors result in the choice of materials that enhance the efficiency of chemical reactions with minimal waste generation.

2.2.4 Cleaner Production

According to UNIDO (United Nations Industrial Development Organization) (1989) and UNEP (United Nations Environmental Program) (1989), Cleaner Production (CP) is the continuous application of an integrated preventive environmental strategy to processes, products and services, in order to increase eco-efficiency and reduce risks to humans and the environment. This approach proposes saving energy and raw materials, minimizing or recycling generated waste and pollution control, in addition to gains related to the improved work of those involved, which are factors that contribute to optimum environmental and economic performance for production processes, even if such factors require joint efforts (ranging from top management to the production sector) to be achieved. It applies to processes,

products and services (WBCSD, 1996; GUNNINGHAM and SINCLAIR, 1997; SOUZA et al., 2008; CNTL, 2003). Its guidelines are geared towards the reduction or substitution of toxic materials in the production process or during product use (WBCSD, 1996). The processes that use CP practices also seek to provide improvements in productivity and economic benefits, through flexible systems, which involve zero-emission goals, continuous improvement toward a closed circuit and adding value throughout the product chain (GUNNINGHAM and SINCLAIR, 1997; SOUZA et al., 2008).

3 Method

In this study, a review was conducted using a variety of sources in terms of approaches that address sustainability and industrial cellulose extraction processes. The working method for the paper was carried out according to the four stages outlined below:

i) Literature review and analysis of bibliography

The literature review was divided into two stages: a study of the characteristics of the kraft, soda and acid sulfite cellulose extraction processes and a study of the guidelines for enhancing the sustainability of processes and product development, in related approaches. Important to declare that pulp extraction is long established and, therefore, mainly published in books. For collecting the information, the following databases were consulted: the library of the Engineering School of UFRGS, Google Books (books.google.com.br), Scielo (scielo.br) and Science Direct (sciencedirect.com). The keywords that were consulted included: cellulose extraction process, chemical pulping, alkaline extraction, acid process, soda process, kraft process, delignification and process additives. During the second stage, the keywords researched were: ZERI Method, Green Supply Chain, Cradle to Cradle, Green Engineering, Green Chemistry, Ecodesign/Design for Environment, DfE, Clean Production and Cleaner Production. More than 100 articles that deal with cellulose extraction processes were identified. The eight approaches most frequently cited in the literature which address improving the sustainability of production processes were recognized. Some approaches were described above. We pinpointed approximately 200 articles and 50 books on the subject, but the most-cited ones were chosen in order to support this work upon an analysis of citations from the literature. The texts with the approaches were compiled and analyzed in relation to the existence of guidelines for improving production processes. The guidelines were cataloged by approach/source, according to the information drawn from the literature in the manner proposed by reference sources.

ii) Definition of criteria for the evaluation of cellulose extraction methods

The set of guidelines generated in the previous phase was reorganized and redundancies were eliminated, creating only one list of guidelines. These guidelines were converted into criteria for evaluating the cellulose extraction processes and compiled in tables, where each criterion is linked to the approaches and authors. The criteria established for analyzing the processes were evaluated and grouped into three categories: selection criteria for material and energy resources; production preparation and adaptation of processes; end-of-life management. In addition, the flexibility of the processes vis-à-vis different types of plant material was evaluated.

iii) Development of an analysis tool for cellulose extraction methods

The criteria established for the analysis of cellulose extraction processes were subjected to evaluation. The tool that was elaborated includes criteria blocks, a two-level scale for the subjective evaluation of each aspect. The answers "met" or "not met" were proposed to express if the industry includes or not that aspect in their processes, also there is a space for comments from the evaluator if the criterion failed to comply. The tool also contains a field for the evaluator to indicate the level of knowledge they have in regards to the extraction process being analyzed, as well as completion instructions, since the space for analysis only includes the operations related to the pulping stage, preparation of the cooking liquor and energy resources used.

iv) Analysis of the cellulose extraction processes and Selection of the method

On the basis of the bibliographic material on cellulose extraction processes, presented in item *(i)* of the method, it was possible to analyze each process in relation to the criteria proposed in the analysis tool from item (*iii*). After the researcher's evaluation, experts, defined by convenience, performed an analysis of the processes vis-à-vis the criteria, in order to confirm the results obtained via the analysis conducted previously from the literature review. Three professionals were interviewed: one of them a technology manager from a Rio Grande do Sul unit of a Brazilian company, that is a world leader in bleached eucalyptus cellulose production using the alkaline process; the other is a production manager of the only Brazilian company that uses the acid process in its operations; and the third is a major consultant to the pulp and paper industry, with training in the area. Based on the analysis of the processes, the one that was most flexible in relation to the raw materials used for cellulose extraction and that also met the proposed criteria, generating pulp suitable for different applications, was selected.

4 Results

The results presented in this article are based on the proposed qualitative method from section 3. The material reviewed made it possible to extract guidelines that can lead to improvements in the economic and environmental sustainability dimensions of production processes and product development. The economic aspects were directly or indirectly considered according to the possibility to avoid wasting material or energy resources as well as time and space in carrying out operations, which represent environment aspects. In addition, reuse capability or maximum efficiency in the use of material and energy resources, with minimized waste generation, was examined. These guidelines bring out economic aspects, since they enable cost reductions in the process. The guidelines applicable to production processes, as per the sustainable approaches studied in the literature review, were then selected. These were arranged according to environmental or economic aspect, related approach and source, as partially shown in Table 1. The entire table may be seen in Seben and Paula (2012a).

Table 1: List of process guidelines from the sustainability approaches and their authors of reference (partial view)

Sustainability aspect	Guidelines	Approaches	Author/Organization
Econ.	Use more economically viable raw materials	GSC, EcoD, GC, CP	9, 20, 19
Env.	Use raw materials from renewable sources	CP, GC, GE, EcoD	11, 6, 5, 21, 8, 19
Env. & Econ.	Ability to use smaller quantities of energy (efficient use)	CP, CP, GC, GE, EcoD, ZERI	11, 6, 5, 21, 12, 4, 1, 13, 2
Env.	Use the least amount of different materials	CP, GE ,EcoD	11, 13, 5, 19
Env.	Reduce or eliminate the use of toxic substances (teratogenic, carcinogenic, etc.)	GSC, C2C, ZERI, CP, CP, GE, GC, EcoD	13, 17, 9, 10, 16, 6, 11, 5, 8, 4, 1, 13, 19, 2, 7, 3
Env.	Choose raw materials that do not generate waste and/or toxic emissions or replace those that do	GSC, C2C, ZERI, CP, CP, GE, GC, EcoD	3, 7, 14, 17, 9, 10, 16, 11, 6, 5, 21, 8, 4, 18, 1, 13, 19, 2
Env. & Econ.	Avoid additional steps in the processes, thus avoiding the additional use of chemical reagents	GC, EcoD	6, 19

Legend: Clean Production (CP); Green Chemistry (GC); Green Engineering (GE); Ecodesign (EcoD); Cleaner Production (CP); Green Supply Chain (GSC); Cradle to Cradle (C2C), Environment (Env); Economic (Econ). **Reference number:** (1) Fiksel (1996); (2) WBCSD (1996); (3) Pauli (1996); (4) Gunningham e Sinclair (1997); (5) Greenpeace (1997); (6) Anastas e Warner (1998); (7) Pauli (1998); (8) Thorpe (1999); (9) EPA (2000); (10) McDonough e Braungart (2002); (11) Anastas e Zimmerman (2003); (12) CNTL (2003); (13) Luttropp e Lagerstedt (2006); (14) Vachon e Klassen (2006); (15) Guimarães (2006); (16) MBDC (2007); (17) Srivastara (2007); (18) Vezzoli e Manzini (2008); (19) Back et al. (2008); (20) Souza et al. (2008); (21) Clean Production Action (2010)

The set of generated guidelines was then reorganized to eliminate redundancies and to propose one single list of guidelines for processes whose economic and environmental aspects are in line with sustainability. After that the guidelines were converted into criteria for evaluating the cellulose extraction processes, which were subdivided into three subgroups (i) Selection of material and energy resources; (ii) Production preparation and adaptation of processes, taking into account waste and emissions control; (iii)

End-of-life management. Seben and Paula (2012b) present the entire criteria table ensuing from the guidelines in Table 2.

Table 2: Partial list of criteria according to environmental and economic aspects

Subgroups	***Criteria***
Selection of material and energy resources	*Use more economically viable raw materials* Use raw materials from renewable sources (...) Use energy derived from renewable resources
Production preparation and adaptation of processes, taking into account waste and emissions control	Ability to use smaller quantities of raw materials (efficient use) Provide the maximum integration of raw materials in the final product – efficiency (...) Avoid additional steps in the process, thus avoiding the additional use of chemical reagents
End-of-life management	Design products with longer life (...) End-of-life product management

The criteria established for evaluating the processes were placed in an analysis tool (see Table 3 partial view) in order to question professionals from the field in regards to the compliance or non-compliance considering the cellulose extraction processes. The researchers have also applied the tool for analyzing kraft, soda and acid sulfite cellulose extraction processes, based on information from the literature. In addition to evaluating the processes in relation to the criteria, they were evaluated in terms of flexibility for use with different types of plant material. Upon receiving the commented responses following the application of the tool combined with the study and understanding of the processes on the part of the researcher, it was then possible to analyze the processes employed. The questions in Table 3, and the items marked as not evaluated by the professionals (interviewees) in the field are commented in the text in italics. A summary of the analysis performed by the interviewees and researcher is found partially in table 3. The complete table may be seen in Seben and Paula (2012c). In light of their extensive knowledge, the acid process was assessed by the professional who works in the industry that uses this process, while the soda and kraft processes were evaluated by the professional who works in a company that uses alkaline processes. The consultant assessed the items in general, once he knows about both processes, arguing that "*in order to analyze the use of sustainable practices in reagent recovery and minimization of emissions, it would be worth analyzing how much the company is able to provide capital and technology resources*." The consultant argues that the items vary according to the technologies adopted by companies and the capital available to improve sustainable approaches.

As per the responses from the experts and the researcher's analysis, the evaluation of the alkaline process industrially applied with the use of additives indicated that most of the above criteria are considered, once the answers "met" was choose. According to the expert, who is the manager in the pulp sector, the criteria presented "*are process management items for complying with sustainability issues that guide the design of new industrial projects.*" The existing industrial facilities seek to recover the reagents used in the cooking liquor and other compounds, as well as thermal energy. The study and questions indicated that "*air emissions are monitored in accordance with current legislation, so as to fit within the required standards*." These standards are not presented in this text but for more information see (CONAMA, 2010) and table is available in Seben and Paula (2012d). The research shows that the soda process does not use sulfur in the cooking liquor, and is thus less selective than the kraft process in attacking lignin, since NaOH is the only delignification agent used for pulping. However, according to the expert that was interviewed, "*the soda process uses less sodium sulfide, but contains salt nevertheless, which is formed through the accumulation of sulfur from the auxiliary fuels in the process cycles*." In the expert's opinion, "*the soda process is not significantly different in terms of sustainability compared to the kraft process, since high investments in more efficient technologies for the recovery and filtration of malodorous sulfur compounds have been made*

in the process using sulfur." However, it should be emphasized that the feasibility of having effective gas filtration systems depends on the capital invested in industrial facilities. Therefore, using a sulfur-free soda process ensures that malodorous sulfur compounds will not be generated. In the entire evaluation done with the tool, only the items referring to long-life product design and end-of-life product management were deemed as not being met. The industry expert claimed that "*the life cycle for the manufacture of cellulose is defined on the basis of its final use and is not generated by the stages of the extraction process.*" In Table 3, these items are shown as not being met, eliciting these comments and explanations. During the evaluation of the acid sulfite process, both through the study conducted by the researcher and the expert's responses, it was verified that neither additives nor process catalysts are used and that alkaline solutions are defined according to greater efficiency and ease of recovery within the process. Also, as occurs with the alkaline processes, gaseous emissions are monitored according to the standards of current legislation. In collaboration with the economic and environmental aspects of the processes, technologies are used for washing the gases and reincorporating them into the process.

Table 3: Analysis of the cellulose extraction processes (Sulfite, Kraft, Soda) in relation to the economic and environmental sustainability criteria (Partial view)

Criteria / Processes		Sulfite		Kraft		Soda	
		Met	Not met	Met	Not met	Met	Not met
Selection of material and energy resources	Use more economically viable raw materials	x		x		x	
	Use raw materials from renewable sources	x		x		x	
	Use the least amount of different materials	x		x		x	
	Reduce or eliminate the use of toxic substances (teratogenic, carcinogenic, etc.)	x		x		x	
	Choose catalytic reagents, as selective as possible		x	x			x
	Choose raw materials that are biodegradable	x		x		x	
	Choose raw materials that do not generate waste and/or toxic emissions or replace those that do	x			x	x	
End-of-life management	Recycle or reuse materials within or outside the process, thereby adding value to them	x		x		x	
	End-of-life product management		x		x		x
Selection of the process	Be flexible for use with different plant materials		x	x		x	

Also, the acid process evaluation of showed the items relating to long-life product design and end-of-life product management were deemed by the acid process expert as not being met. According to the interviewee, "*the final application of the cellulose pulp and its end-of-life will not be defined by the industry operating the extraction process or be under its responsibility*." Based on the literature review and the interviewee, the most recommended alkaline solutions to use in the acid sulfite process are ($Ca(OH)_2$) and magnesium ($Mg(OH)_2$). According to the expert, the consultant to companies in the sector, "*if an alkaline solution with Ca is used in the cooking liquor, the residual liquor rich in Ca and lignosulfonates is sold for application in other high added-value products. Only then is it feasible to use Ca, since the reagents cannot be recovered in the process due to incrustation problems*". The literature review showed that the constituent materials of the cooking liquor include: dissolved lignin, lignosulfonates, degraded carbohydrates, calcium and magnesium sulfate, extractives and resins, among others. In the case of applying the bisulfite process with an ($Mg(OH)_2$) solution, it is feasible to recover the latter by burning magnesium oxide (MgO) and sulfur dioxide (SO_2) in the recovery boiler, whose recombination allows the cooking liquor to form. The literature review indicated that the use of alkaline solutions with Na or $NH4^-$ is not feasible due to the difficulties in recovering the reagents and their high cost. As noted above, the air emissions from both processes are monitored via current legislation. In the kraft alkaline processes, the most critical compounds to control are the reduced sulfur compounds, while in the acid processes hydrogen sulfide (H_2S) is the most strictly controlled.

The literature review also indicated greater flexibility in terms of using different raw materials for cellulose extraction through alkaline processes. These processes also permit the use of process additives that help

in the selectivity of the reactions and cellulose preservation. In addition, the economic and environmental sustainability aspects are bolstered by the fact that the process allows the cooking liquor to be reused both for forming new liquor and power generation. Besides that, energy efficiency is remarkable. The acid process, in turn, also provides energy efficiency and pulp with a high degree of delignification, but the choice of materials and reagents is limited.

In light of what's been shared, the industrial sector is striving after technology and the selection of reagents for adapting processes to sustainability requirements. Compliance with the different criteria demonstrates that the sector's performance has been improving in order to conform to sustainable practices. One aspect worth mentioning is that the technologies for controlling greenhouse gas emissions, as well as recovering reagents and energy within the process, are becoming increasingly sophisticated. However, the incorporation of these new technologies by industries in the sector depends on the capital invested by the industry. On the basis of the information collected and studied from many bibliographical sources, and via professionals from the sector, it was possible to assemble the information in a process summary table for the purpose of selecting the most flexible one with different plant materials and in line with the sustainability aspects addressed. The analysis of the extraction processes for selecting the most appropriate one according to the criteria that were broached is a subjective task and difficult to carry out, since it depends on investments in technology and the availability of capital to do so. However, in view of the materials studied and the experts who were questioned, the analysis resulted in the choice of the soda process as the most suitable one for application in extracting cellulose from different lignocellulosic plant sources. The process is applicable to various plant sources, and its selectivity can be improved through the use of additives, without the drawback of generating malodorous compounds.

5 Conclusion

This paper presented the main approaches dealing with sustainability applicable to product and process development. Industrial cellulose extraction processes were also investigated. In view of the guidelines established by the approaches, analysis criteria were defined for current industrial processes. These were analyzed according to the criteria from the literature review conducted by the researcher and through inquiries with professionals from the sector. The sustainability approaches, with an economic and environmental focus, list practices for reducing negative environmental impact, such as: emissions control, efficient use of material and energy resources and waste minimization or reuse. In line with such guidelines, companies have been striving to comply with these factors. The analysis of extraction processes for selecting the most appropriate one resulted in the choice of the soda process in that it complies with most of the sustainability criteria and is also applicable to different lignocellulosic plant sources. In selecting processes and verifying compliance with sustainability criteria, it is worth noting that improvements often depend on the company disposing of financial resources to invest in its projects and processes through the acquisition of technologies and materials. Likewise, customers, for whom the products are intended, need to be aware of sustainable practices so that the results can be optimized. Opportunities for further improvement may lie in the path of greater energy recovery and emissions control, since the recovery of material within the process is already well represented.

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