Technical and marketing criteria for the development of fast pyrolysis technologies.

Juan Miguel Mesa Pérez
Bioware Tecnologia
juan@bioware.com.br
55 (19) 99799-1464
55 (19) 3579-9423

Felix Fonseca Felfli
Universidade Metodista de Piracicaba – UNIMEP
fffelfli@hotmail.com
55 (19) 3124-1777

Summary

The management of projects regarding the use of biomass requires human resources with specific technical knowledge and tools to assess the real potential of raw materials within one or several production chains. Storage and transportation logistics, conservation and handling of the biomass, available technologies of transformation, and consumer market for the products are critical stages in the management process. The following chapter will present the technical, financial, and market criteria for managing production chains that use biomass as raw material in processes of fast pyrolysis.

1. FAST PYROLYSIS: COMPOSING ELEMENTS OF THE PRODUCTION CHAIN

1.1. Biomass thermo-conversion processes

The thermo-conversion processes are aimed at transforming solid biomass into new solid, liquid, and gas products of greater aggregate value. The distribution of the new products from this transformation will occur according to the quantity of oxygen involved in the thermo-chemical reactions and the temperature of the process. For example: in the combustion process, thermo-chemical reaction occurs in stoichiometric conditions that correspond approximately to the band of (6-7) kg of air/kg of dry biomass. In this process, the intended product is the heat from the combustion reaction. As the quantity of air in relation to the stoichiometric value decreases, the main primary product changes, as indicated in Image 1.1.

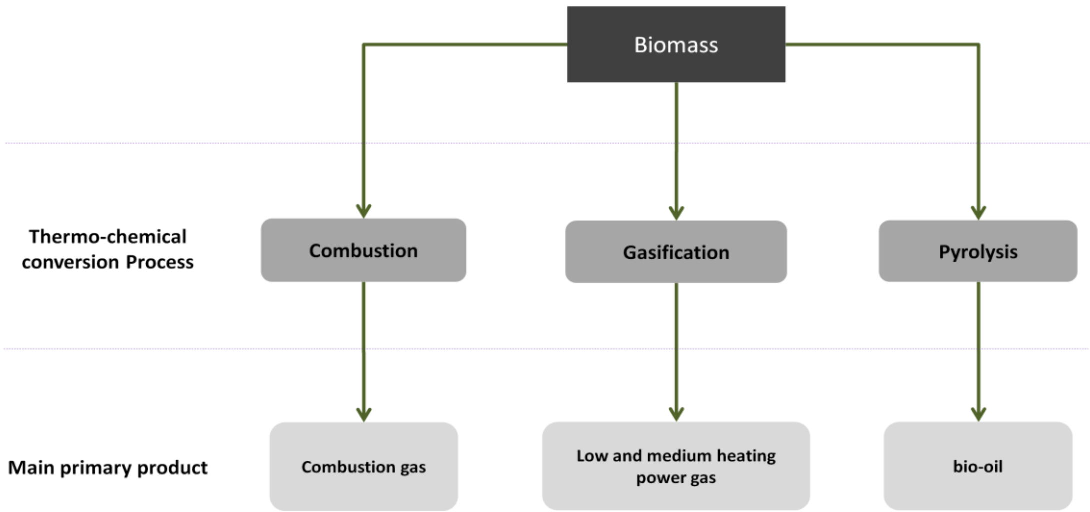


Figure 1.1- Intended products in the thermo-conversion processes.

Fast pyrolysis of biomass is defined as the thermal degradation of organic material in the absence of oxygen for the production especially of bio-oil. Charcoal and gases are also produced during this process.

1.2. Production Chain of Biomass Transformation

Pyrolysis is only one element in a series of interconnected stages that compose what we have defined as the Production Chain of Biomass Transformation – PCBT. This can be divided into three primary elements (Image 1.2):

1. Raw material;
2. Transformation Technology;
3. Consumer market.

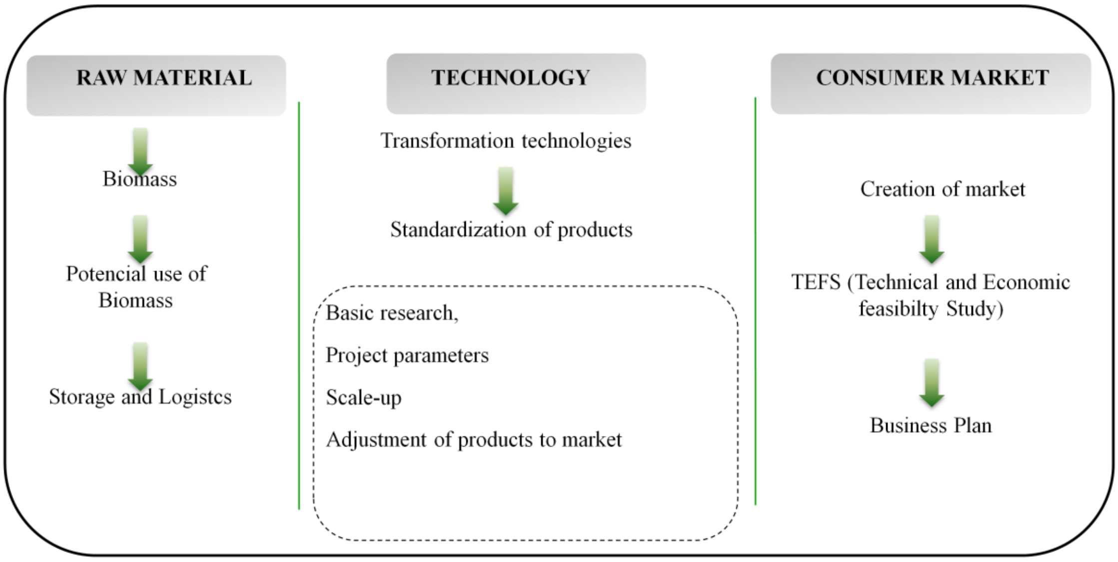


Figure 1.2- Composing elements of the Production Chain of Biomass Transformation – PCBT

Regardless of the PCBT used to elaborate a business plan, there are requirements that characterize the investment risks, which we list below according to the PCBT's primary elements.

Raw Material

"Good biomass is that which ensures":

- ✓ Large scale supply (from 100 ton/day);
- ✓ Standard quality (size, shape, and composition);
- ✓ Absence of environmental restriction;
- ✓ Competitive prices (defined by a sensitivity analysis).

Transformation Technology

The investment risks of innovative technology are directly related to the experience accumulated by the technical team involved in all the stages of the development, from the pilot to the demonstrative commercial scale. The rigorous definition and standardization of procedures and methodologies for obtaining the products, as well as the definition of project parameters and scale-up of minimize the risks by ensuring:

- ✓ The stable operation of the technology's composing equipment,
- ✓ Processed products which are made standard according to consumer market,

Consumer Market

The largest risk element in PCBT is when the consumer market is inexistent or under development.

The product that will be inserted in the consumer market, in most cases, intends to replace already existing fuels and/or inputs, which are generally derived from petroleum. Adjustment of pyrolysis products to the final consumer in the most effective way possible supposes the need to minimize the incompatibilities between biomass- derived products and petroleum-derived products. In other words, this adjustment must create standardized fuels. This requires the conduction of appropriateness and adjustment tests on pyrolysis products alongside the final consumer.

Regardless of the environmental gains that may come from the use of a green technology, the determining factor nowadays is the product's final price in relation to other existing products in the market. A good approach consists of ensuring that prices are 10% lower in comparison to equivalent petroleum-derived products.

1.3. PCBT Logistics

A deeper analysis of the composing elements of PCBT and its risks indicates that the predominant factor for ensuring a project's success in the transformation of biomass is the logistics associated to each element of PCBT. Image 1.3 illustrates this logistics.

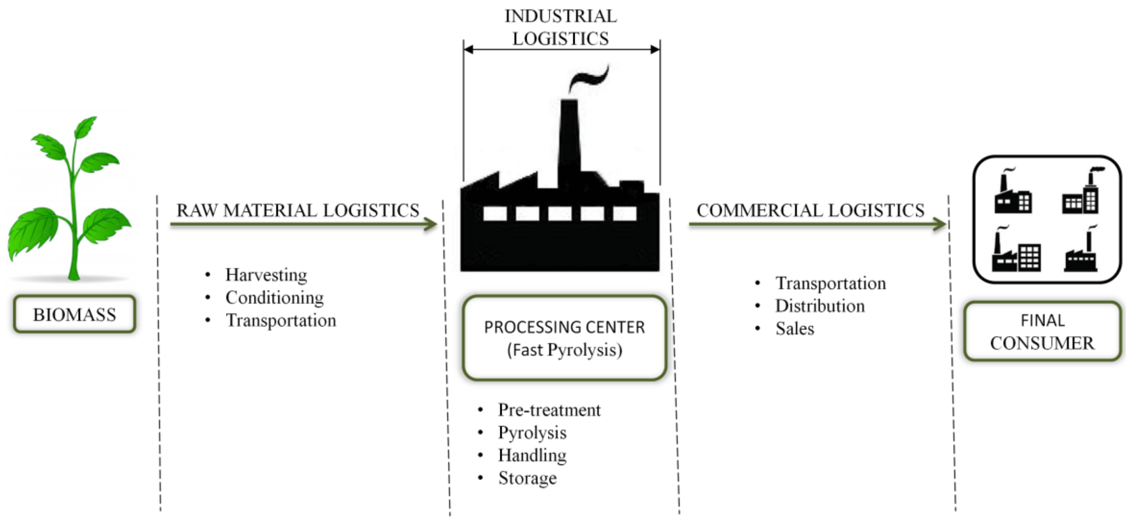


Figure 1.3- Logistics chain

- ✓ Raw material logistics: involves harvesting, conservation, and transportation to the transformation center,
- ✓ Industrial logistics: involves the pre-treatment of biomass, pyrolysis, handling, and storage of pyrolysis products.
- ✓ Commercial logistics: involves transportation, distribution, and sale of pyrolysis products.

Pyrolysis is a process whose final goal is to solve the logistics problems associated to the "in natura" use of biomass. In the next topic we will discuss the criteria for the analysis and management of the composing elements of PCBT.

2. CRITERIA FOR THE ANALYSIS OF RAW MATERIAL

2.1. Logistics versus origin.

Since the beginning of mankind, human beings have used biomass (wood) as fuel for heating and cooking their food. With the development of modern society, the use of biomass as fuel was transformed and the use of forests for generating energy was discontinued in order to prioritize biomass sources that are not in conflict with the balance of nature, such as the so-called biomass residues. Biomass residues may be classified in several ways. Following the goals of this paper, we will classify them here according to their origin, as shown in table 1.

Table 1 - Biomass classification

Origin	Type of Residue	Definition
Forest	Forest residues	Biomass obtained from planted forests for energy-generating uses or not. They result in branches or logs inferior to 8 cm in diameter.
	Residues from wood processing	Wood chips, shavings, and sawdust resulting from the processing of wood for the production of furniture and other wood artifacts.
	Residues from recovered wood processing	Residues produced from wood recovered from social-economical activities that employ materials originated in forests. For example, construction wood and wood from packaging and pallets.
Non-Forest	Energy-generating plantations	Biomass obtained from energy-generating plantations, such as sugarcane, elephant grass, sorghum, and others.
	Agricultural Residues	Residue generated during the harvest of agricultural products such as the straw from sugarcane, rice, soy, corn, among others.
	Agro-industrial Residues	Residues generated during the agro-industrial processing of different crops, such as sugarcane bagasse, rice shells, peanut shells, soy shells, and others.

The logistics of biomass may be divided in two phases:

1. Harvesting, transportation, and storage logistics;
2. Conservation for the use in the transformation center logistics.

The operations that must be considered in harvesting, transportation and storage logistics are defined by the origin of the biomass, as detailed in Table 1, in the sequence, a detailed analysis of the materials classified as non-forest is presented.

- **Energy-generating plantations**: In the handling of this kind of bio-fuel the logistics of planting, harvesting, transportation, handling, and storage of biomass to the processing center needs to be considered. The costs and the complexity of the logistics involved are extremely high and justified only in large-scale projects such as, for example, the production of ethanol, which has a national market and therefore justifies the investment. However, ethanol’s case must be seen with caution because it involves historical and political factors that contribute positively to its success.

- **Agricultural Residue:** This kind of residue is usually found in the field. Therefore it is necessary to plan logistics that will take the harvesting, handling, and transportation of these residues from the field to the process center into consideration. Example: sugarcane straw.

- **Agro-industrial Residues:** This kind of residue is generated in agro-industries and is concentrated in the transformation center. Example: sugarcane bagasse.

The comparisons indicated above make it possible to conclude that not all non-forest residues potentially available may be considered as a business opportunity because the costs with harvesting, transportation, storage, and conservation logistics may prove to be excessively expensive.

2.2. Environmental restrictions for the use of biomass

Social-environmental aspects may also create restrictions for the use of non-forest residues and must be taken into consideration when analyzing their potential use. For example, energy-generating plantations may compete directly against food-producing plantations creating a conflict with the concept of second generation bio-fuel.

In the case of agricultural, it is important to highlight that some of them must be maintained in the soil since they are necessary for the conservation and nutrition of the soil. For this reason, their indiscriminate removal may also present environmental restrictions.

Regarding social-environmental aspects, it is important to observe that the energy-generating plantations compete directly against food-producing plantations creating a conflict with the concept of second generation bio-fuel. It is for this reason that not all energy-generating cultures may be considered as an available resource. On the other hand, agricultural residues also present some environmental restrictions because their indiscriminate use can create a substantial decrease of organic material and soil nutrients.

Concerning agro-industrial residues, social-environmental restrictions are related to the final disposal of residues and their impact on the environment.

Example 1: Residues whose availability is for the use in combustion processes. In this case, particulate and ash emissions are what constitute an environmental restriction.

Example 2: Rice Shell and sawdust, largely used as chicken beds, become contaminated with microorganisms, viruses, and other substances at the end of their use, constituting an environmental restriction.

Example 3: Processes in which biomass is used partially, creating liquid and solid contaminants. For example, bio-digestion and hydrolysis processes.

2.3. Standardized quality of biomass

Vegetable biomass is composed basically of celluloses, hemicelluloses, lignin, and extractives as well as inorganic matter (ashes).

When element analysis is conducted, it is possible to observe that the level of oxygen is around 35 to 50% in mass, carbon between 35 and 50%, and hydrogen between 5 and 7%. Therefore, biomass is an extremely oxygenated compound, a factor which contributes negatively to the product’s energetic density. Due to these characteristics, the Higher heating value (GCV) of biomasses is around 13,000.00 to 20,000.00 kJ/kg, practically half of any petroleum-derived fuel, which present very little or no oxygen in its element composition.

In addition to this, the apparent bulk density of biomasses (bagasse, straw, Grass, sawdust, rice shell, agro-industrial residues) stays around 80 to 600 kg/m3 and the level of moisture between 30 and 50%. These physical-chemical characteristics make biomass a fuel of low energetic density, causing it to have low portability (low capacity for transportation) and requiring the use of high volumetric capacity equipment for its transformation. This makes its large scale use unfeasible compared to fossil fuels. These reasons justify the need to know the physical-chemical characteristics when assessing the potential of a biomass source. Below, we will analyze some of the physical-chemical characteristics and their influence in biomass potential.

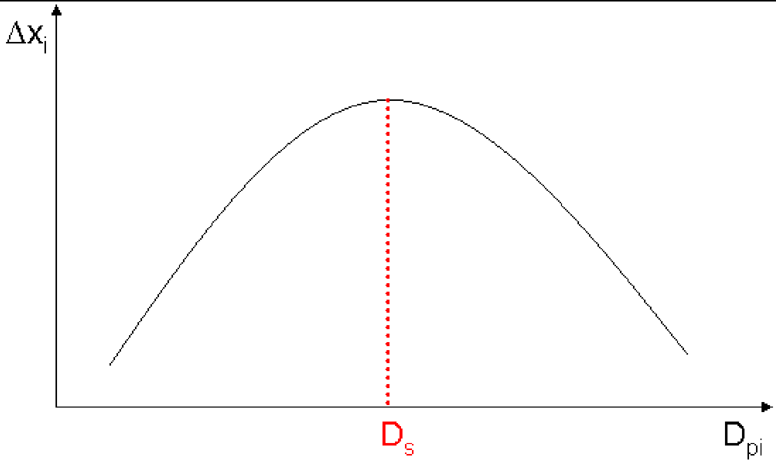
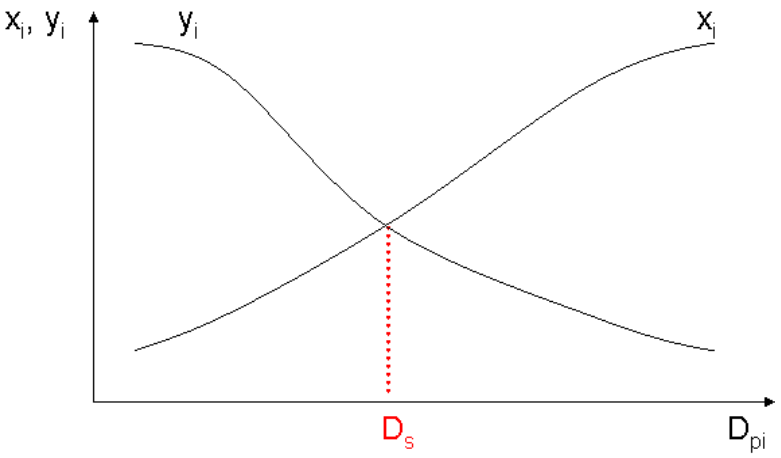
Moisture: It is the level of water which is not linked to the biomass’s chemical structure and is incorporated into the agro-industrial processes, such as in the case of bagasse, or in natural forms, as is the case of sugarcane straw. Moisture influences the biomass’s energetic density and the effective level of available fuel energy (Lower Heating Value) negatively. For instance, the combustion processes that use humid biomass not only consume energy to evaporate the moisture, but also have an additional expenditure to overheat vapor to the operation temperature of the combustor. In the case of pyrolysis, an additional expenditure of energy is also generated not only in the pyrolysis reaction, but also in the later drying process of liquid fractions. Traditional drying eliminates biomass moisture through its evaporation at temperatures above 100^{o} C and consumes part of the biomass's primary energy.

Therefore, moisture can be a determining factor when choosing the type of biomass to be transformed since the energetic cost to eliminate it may be a decisive factor in pre-treatment logistics.

Homogeneity: Biomass is naturally polymorphic and transformation processes such as fast pyrolysis require materials in a homogeneous state and therefore need grinding and milling processes as part of the unit operations of the pre-treatment. Segregation is a frequently observed phenomenon when biomass is ground and/or milled. A first fraction in the form of a powder precipitates in the inferior part of the packaging and in the superior part a second fraction in the form of a fiber can be identified. Statistically, when this happens, we can say that there are two populations, i.e., the sample is heterogeneous and any physical-chemical analysis must consider both populations independently. Determining the ashes content in heterogeneous biomass is a kind o analysis that experiences great dispersions. This happens because the frailty of the constituting parts of plants and grasses is variable. During the grinding in mills, the more fragile part of biomass presents itself in the form of a powder and the most resistant one in the form of fibers. The powder fraction in general concentrates the larger quantity of ashes. Biomass that presents high segregation may not be viable as raw material for pyrolysis.

Three methods used to determine the average diameter of particles when granulometric distribution follows a normal distribution, i.e., when the particles are distributed in a single population, are presented below.

Table 2- Methods for determining the particle size.

Methods	
Mathematical equation	$$D_s = \frac{1}{\Sigma\, \Delta x_i / D_{pi}}$$
Differential Curve	 *Curve Δx_i versus D_{pi} (normal distribution)*
Cumulative curve	 Curve x_i, y_i versus D_{pi}.

It is advisable that the differential curve be represented graphically in order to verify if the data is distributed in a normal way. In work with biomass, normally the curves are bimodal and in this case the result of the average diameter is different for each method applied. This happens because bimodal curves indicate the existence of more than one population within the analyzed samples and any method applied, be it graphic or using equations, is not rigorous. When the data is distributed in a normal way, the value obtained for the diameter of particles is approximately the same in any method described.

Ashes content: The ashes content represents the quantity of inorganic material incorporated to the biomass in a natural way or acquired during the harvesting, handling, and transportation logistics. The ashes may possess expressive quantities of potassium, calcium, and phosphorous, among other components. The calcium and potassium oxides, when mixed with inert material used in fluidized beds, reduce the melting point creating problems in sintering. On the other hand, an excessive ashes content limits the organic fraction present in biomass, damaging the yield from liquid products of pyrolysis.

Bulk density: Biomass, depending on its origin, presents bulk densities at the (80-500) kg/m3 range. Low bulk densities generate high logistics costs both in the raw material and in the use of the installed capacity in the transformation center. An example of this comes from the high investments in supply systems in pyrolysis technology.

Chemical composition: The chemical composition is analyzed in terms of element composition and immediate analysis. Element composition measures the content in percentage of carbon mass (C), hydrogen (H), sulfur (S), oxygen (O), nitrogen (N), moisture (W), and ashes (A). This characterization constitutes the base of stoichiometry calculations and, consequently, it determines the limit volume of air that must be injected in the pyrolysis reactor. The immediate composition analyzes the level of fixed and volatile carbon in the biomass. The level of volatiles determines the yield of the liquid and gas products in pyrolysis.

3. CRITERIA FOR ANALYSIS AND INDUSTRIAL LOGISTICS MANAGEMENT OF PYROLYSIS.

3.1. Pre-treatment of solid biomass

Biomass needs to be pre-treated so that its characteristics are adjusted to the requirements of the fast pyrolysis process. Traditionally, pre-treatment concerns the adjustment of granulometry and moisture in the biomass to the conditions of the process. The number of unit operations to be performed during pre-treatment depends on the physical-chemical characteristics of the biomass and the quality parameters required in the transformation process.

As an example, image 3.1 shows the flowchart of a pre-treatment process for forest residues with 8 cm average diameter and 50% moisture. The process of fast pyrolysis requires particles between 2 and 4 mm and moisture between 10 and 15%. In order to reach these conditions, the pre-treatment of this residue involves four unit operations and fifteen pieces of equipment:

1. Cutting of logs
2. Milling of humid residues
3. Drying of residues
4. Re-cutting of residues

Pre-treatment logistics for wood residues for the use in rapid pyrolisis processes may be seen with criticism due to the great number of unit operations and equipment involved, which reflects in high costs per ton of biomass.

The costs of pre-treatment may be expressed through the sum of individual costs for each unit operation as can be seen in equation 3.1.

$$C_{PT} = \sum_{i=1}^{n} C_i \qquad (3.1)$$

Where:

C_{PT} – Cost of pre-treatment (R$/t)

C_i – Cost of each unit operation in pre-treatment (R$/t)

Unit costs include operational costs, variable costs, fixed costs, and depreciation of machinery.

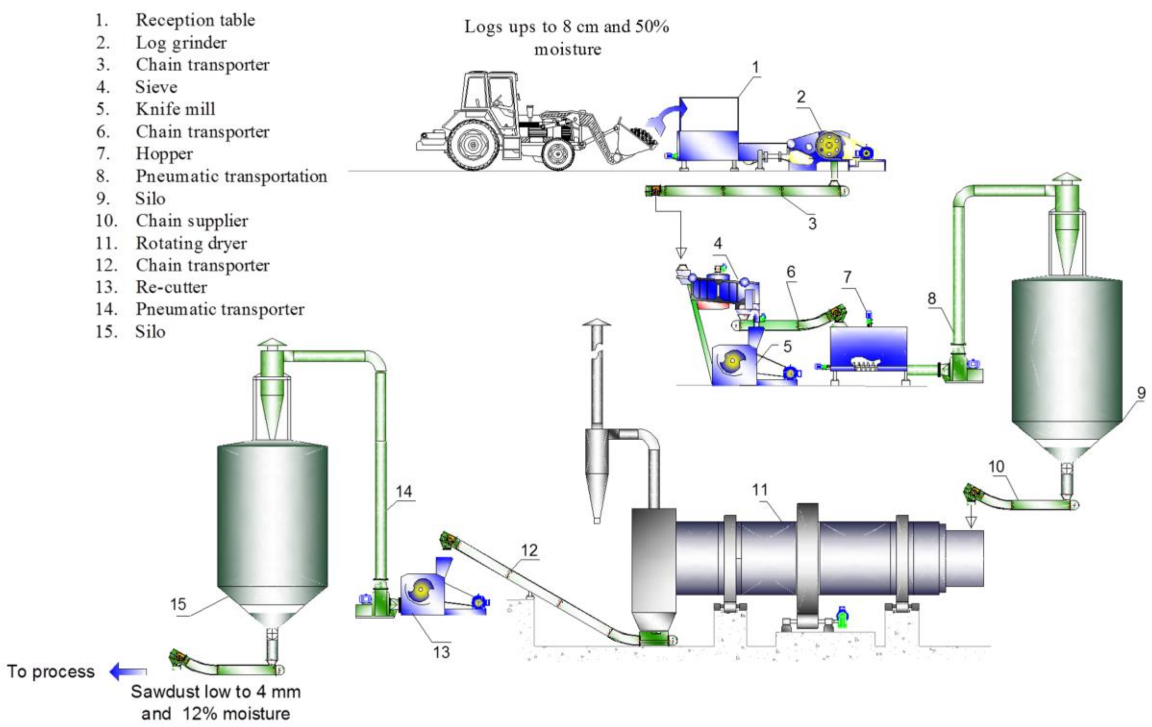


Figure 3.1- Flow chart of pre-treatment process

Table 3, shows the relation between biomass origin, unit operations, and the costs involved in pre-treatment.

Table 3- Unit operations and cost.

Origin	Type of residue and physical-chemical characteristics	Number of single operations	Approximate pre-treatment cost
Wood	Branches and logs under 8 cm in diameter, 50% moisture	1. Cutting of logs 2. Milling of humid residues 3. Drying of residues 4. Re-cutting of dried residue	85 R$/t
	Sawdust with average granulometry of 5-6 mm 25% moisture	1. Drying 2. Milling	50 R$/t
Agricultural	Sugarcane straw, 25% moisture	1. Cutting of straw 2. Drying of saw 3. Milling	70 R$/t
Agro-industrial	Rice shell	No unit operations	0 R$/t

Figure 3.2 ,shows the main cost centers that are part of industrial

logistics for the pre-treatment and pyrolysis of biomass.

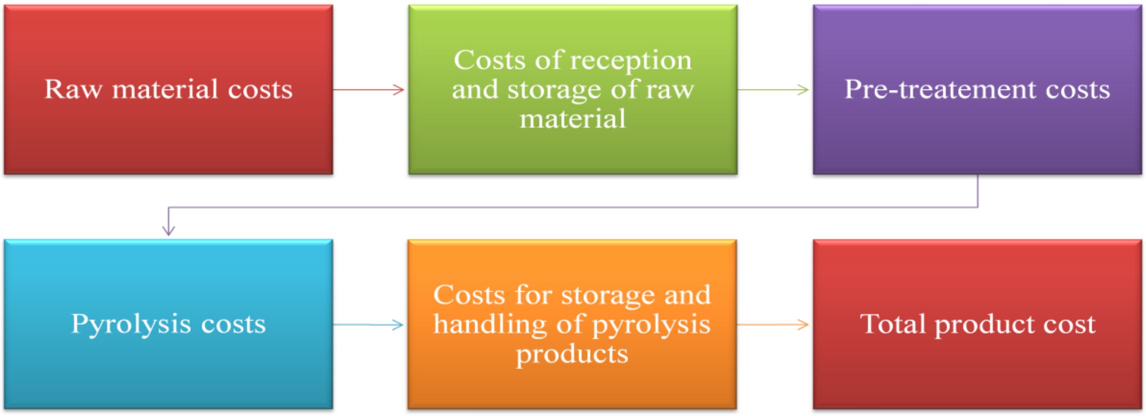


Figure 3.2-. Cost centers

Pre-treatment costs may be higher than pyrolysis costs. Table 4, shows the detailing of the costs involved in the fast pyrolysis process of forest residue as an example.

Table 4- Detailing cost of fast pyrolysis.

Description of cost centers	**Value (R$/t)**	**Percentage (%)**
Raw material: Forest residues (50% moisture)	25	10,6
Pre-treatment: Cutting of logs, milling, drying, re-cutting	85	36,2
Pyrolysis: Pyrolysis and separation of products	100	42,6
Storage of pyrolysis products (bio-oil and charcoal)	25	10,6
Total	235	100

3.2. Standardization of solid biomass

The traditional pre-treatment process promotes only physical transformations, therefore there are no changes in the biomass's chemical structure and even some physical properties like the visco-elastic properties are not substantially altered. For this reason, the use of different types of biomass in the same transformation unit is complex or even unfeasible. Traditional pre-treatment does not ensure a physical or a chemical standardization for solid biomass. Table 5, illustrates the significant variation of physical-chemical properties of different biomasses.

Table 5 **-**Physico-chemical characteristics of biomass.

Biomass	Element Composition (%)						Moisture "in Natura" (%)	Bulk Density (kg/m^3)	Lignin level (%)
	C	H	O	N	S	A			
Eucalyptus residues	49,00	5,87	43,97	0,30	0,01	0,72	35	250	24,68
Rice shell	40,96	4,30	35,86	0,40	0,02	18,34	12	110	14,30
Sugarcane bagasse	44,80	5,35	39,55	0,38	0,01	9,79	50	100	18,26
Cotton residues	47,05	5,35	40,77	0,65	0,21	5,89	35	80	0

Reference: Jenkins, 1990

The torrefaction process is a treatment that makes it possible to accomplish controlled physical-chemical transformations and is, therefore, an effective way to standardize biomass in its solid state. Standardized Solid Biomass (SSB) is a new concept proposed here to be used in the characterization of biomass groups that present similar physical-chemical properties after their pre-treatment (image 3.3).

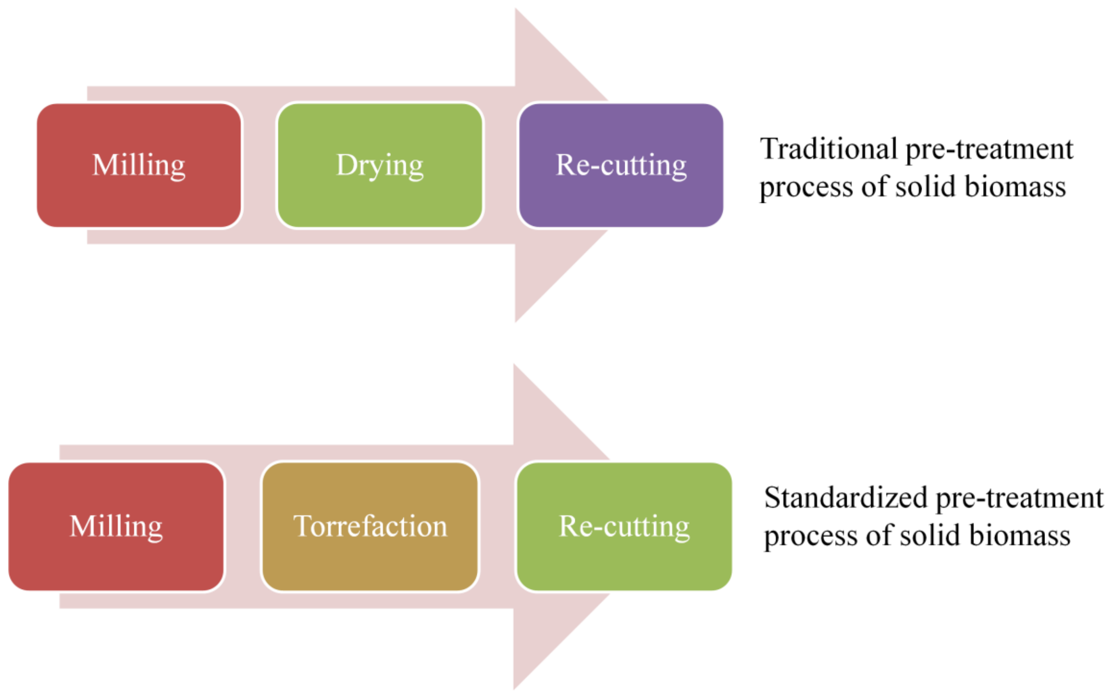


Figure 3.3- Unit operations in the traditional and standardized pre-treatment process

Torrefaction of biomass develops between 220 and 330^o C (Schwob, 1985). Under these conditions, moisture is removed and hemicelluloses is degraded causing the release of acetic acid, fractions of phenol, and other low calorific power compounds. Lignin and celluloses suffer slight degradation. The conversion yielding varies between 60 and 80% due to the temperature conditions under which the process is done (Antal, 1991; Doat J, 1985).

During torrefaction, two types of reactions, classified as thermo-condensation and carbonization reactions, can be identified (Bourgeois, 1989; Marcos Martin, 1989). Carbonization is kinetically slow in the thermal domain of torrefaction, but can increase abruptly above 250^{o} C with strongly exothermal reactions, which may possibly lead to an uncontrolled increase in temperature and consequently to total carbonization of the material. Therefore, in order to ensure that the process will develop in the required thermal domain it is necessary to evacuate the heat generated during the parasite reactions of carbonization.

The properties of torrefied biomass vary according to the time and temperature of the processing (Bourgois, 1984). Torrefied biomass presents the following properties:

- ✓ High energetic density: Free and linked water is eliminated and high energy level volatiles are preserved in the solid increasing in up to 20% the biomass's calorific power.

a) Hydrophobia: Due to physical-chemical transformations, the re-absorption of moisture is practically non-existent during storage. Balance moisture stabilizes at around 3%.

b) Friability: Torrified biomass fibers lose their elastic properties and become friable material that can be ground or re-cut into very thin particles (in the form of powders) with low energy consumption and in a homogeneous form.

Table 6, shows the characteristics of torrified eucalyptus wood under different conditions of temperature and time of residence (Felfli F.F., et alii, 1999; Felfli F.F., 1999).

Table 6- Characterization of torrified wood residues.

Temperature (^oC)	Time (hr)	Volatiles (%)	Fixed Carbon (%)	Ashes (%)	HHV (kJ/kg)
220	0,5	75,2	18,2	6,6	20426
	1	74,6	19,0	6,4	20989
	1,5	73,6	19,8	6,6	21065
250	0,5	65,2	27,0	7,8	21209
	1	65,0	27,2	7,8	22061
	1,5	60,0	32,1	7,9	22674
270	0,5	55,7	34,6	9,7	22772
	1	52,1	38,2	9,7	22981
	1,5	41,0	49,2	9,8	23066

Reference: Felfli F.F., 1999

Controlling torrefaction parameters allows for the production of fuel with a predefined physical-chemical standard regardless of the origin and initial composition of the biomass. It is important to highlight that the ash content is the only component that cannot be altered through the process.

The advantages of the standardization process via torrefaction are:

- Homogeneous physical-chemical properties: Raw material fed into the pyrolysis reactor has a homogeneous standard that makes the supplying and controlling of operational parameters in the reactor easier.
- More efficient use of installed capacity in the reactors: Due to the increase of the terrified biomass's energetic density, pyrolysis units can use installed capacity more efficiently.
- Improved fluid dynamics: Due to the high level of friability of terrified biomass, it is possible to decrease the size of the particle in a homogeneous way. This minimizes the appearance of undesirable phenomena such as sintering, segregation, inefficient mixture between the inert bed and biomass, and inadequate de-volatization of biomass.
- Higher quality bio-oils: Torrefaction process eliminates free and linked water from the biomass's structure as well as volatiles of lower energetic level, especially acids. It also concentrates the level of lignin. This makes it possible to obtain low-acidity, low-moisture, and low-viscosity bio-oils during pyrolysis since the improvement in fluid dynamics renders chemical degradation more efficient and makes the size of the chemical chains of components smaller.

The standardization process of biomass through torrefaction can contribute significantly to the improvement of industrial logistics in the process of fast pyrolysis, decreasing costs and increasing the efficiency of the process and the quality of pyrolysis.

3.3. Technological bottlenecks for fast pyrolysis

A machine's availability and reliability are determining factors in terms of cost and efficiency in industrial logistics. Below, we will analyze the main technological bottlenecks that define availability and reliability in the technologies of fast pyrolysis.

1. **Feeding of non-standardized biomass,**

Non-standardized biomass creates a series of negative effects such as:
-Leakage of gas through the feeding system
-Fluctuation of feeding capacity
-Fluctuation in the yielding of pyrolysis products

2. **Biomass mixture – inert;**

An adequate mixture between inert material and biomass avoids the segregation phenomenon. Biomass may be segregated in the inferior part of the bed or on the surface. In both cases the bed's temperature increases rapidly in the area where the biomass layer is segregated. If the surface speed of gas is close to the speed of minimal fluidization, the biomass layer is formed in the superior part of the bed. For gas surface speeds that are greater than the speed of minimal fluidization, there is an inversion of layer, i.e., biomass is segregated in the inferior part of the bed. The mapping of the mixture regime according to M.G. Rasul (1999) can be done from the study of the graphic behavior between d_{pb}/d_{pI} vs ρ_{pb}/ρ_{pI} (where d_{pb} is biomass particle diameter, d_{pI} is inert particle diameter, ρ_{pb} is biomass particle density and ρ_{pI} is inert material apparent density). See image 3.4.

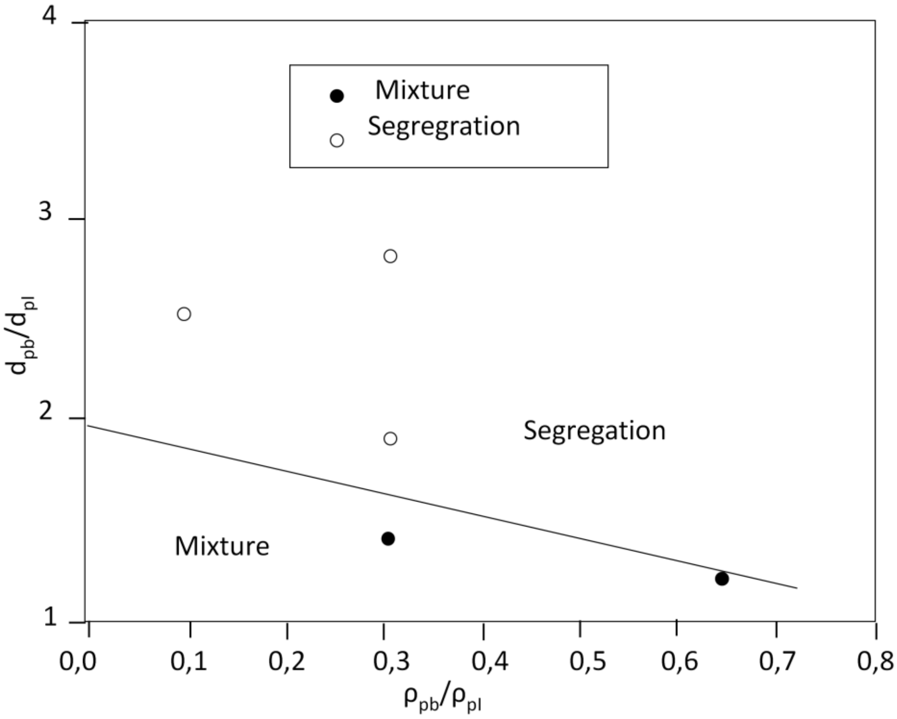


Figure 3.4.- Mixture and segregation in fluidized bed (sand and bagasse).

3. **Residence time of vapors,**

Time of residence of vapors should be the least possible to avoid secondary reactions among the solid, liquid, and gas components. This situation causes the qualities and yielding of products to be different. The estimated time of residence must be counted from the moment de-volatization occurs until their separation at room temperature. Although part of pyrolysis vapors condensate at high temperatures (200-400^o C), because they have micrometric particle sizes they do not sediment. The combination of cooling processes and mechanical separation of mists is used to decrease the time of residence in these liquids in the vapor phase.

4. **Fractioned separation of products**

De-volatization of biomass creates three phases: first a solid phase (charcoal); second a condensable vapor phase (mixture of organic products); and third a gassy phase. The pyrolysis process aims at optimizing the obtaining of liquids from the vapor condensation phase. In pyrolysis, vapors are collected fully in the liquid form and with a complex chemical composition where over 200 different compounds may be found. The separation of specific chemical species from the condensed liquid through thermal fractioning is inefficient since approximately 35% of liquids turn solid (tar or coke) when heated at temperatures above 200 ^{O}C, making it impossible to separate the fractions of interest efficiently.

5. **Clogging of tubes and equipment,**

Avoiding condensation of liquids in the tubes is advisable in order to prevent clogging and increase in pressure in the pyrolysis reactor. When this is not possible, the use of mechanical actuators to eliminate the build-up of material is indispensable to avoid halts in the process.

6. **Scale-Up.**

Although fluidized bed reactors like combustion and catalytic cracking are being utilized frequently in commercial operations, engineers still face uncertainties when they develop new commercial projects. Typically, the development of processes takes place in discontinuous units in the laboratory, pilot plants, and large demonstrative units levels.

Many of the operation’s important characteristics may vary in units of different sizes. This is a critical problem for the broadening of the scale (*scale-up*). In other words, it is difficult to anticipate with precision a plant’s performance when the size is changed so that a commercial plant can have a satisfactory performance.

These problems may be related to insufficient gas flow rate, inappropriate mixture of solids in the bed, and operational problems (MATSEN, 1985).

If the degree of mixture and the efficiency of the gas-solid contact are maintained constant between beds of different dimensions, then the thermal characteristics and the speed of the chemical reaction must also be similar. However, in general, the bed’s fluid dynamics might not remain the same. Scale-up involves the understanding of changes in fluid dynamics and how these changes influence the thermal and chemical conditions through the variation in the gas-solid contact, time of residence, circulation of solids, and mixture and distribution of the gas. Until there is a better understanding of the phenomenon or a complete verification of the equations is done, numerical models cannot be used to describe the fluid dynamics of these systems. Therefore, the numerical models alone cannot be considered reliable tools for the scale-up of plants.

The use of experimental planning in small scale makes it possible to simulate the fluid dynamics of pilot or commercial reactors directly. Different diameter reactors, geometry, and conditions of operation can be simulates in the laboratory through these modeling techniques.

The empirical mathematical models derived from the experimental planning describe the main characteristics of a product’s or process’s quality in a limited experimental area. For each experimental condition, there is a group of non-dimensional numbers that define the system’s behavior (for example, Reynolds, Froude, Archimedes, etc.). The relations of scales obtained after the parameters have been equaled in plants of different sizes allow the estimation of the effect of the change in scale (models corrected by the change in scale) if they are incorporated to the adjusted mathematical model. The difference between the values of the responses predicted by the adjusted mathematical model and the corrected one is called distortion. The use of experimental planning reduces incompatibilities between systems of different sizes.

4. CRITERIA FOR MARKET ANALYSIS

4.1. The main paradigms of PCBT

The introduction of pyrolysis products in the market requires the breaking of paradigms in different aspects of this PCBT. Some of these paradigms are:

1. Not very rigorous evaluation of energetic potential among fossil fuels and biomass derivates;
2. Extrapolation of technological and market knowledge logics of petroleum derivates to pyrolysis products.
3. Both petroleum and bio-oil are fuels. However, “bio-oil is not petroleum”.
4. Market and bio-oil regulation according to the same rules used for petroleum and derivates.

4.2. Strategies for consumer market insertion of pyrolysis products

The insertion of new pyrolysis products in consumer markets is defined by the strategic alliance between the company detaining the pyrolysis technology and the final potential consumer or residue generator. Below we list the components of the action plan to create one or several success cases.

MANAGEMENT OF STRATEGIC ALLIANCE

- Identification of partners among the potential clients.
- Negotiation of partnership to install and operate a demonstrative commercial scale unit.
- Follow-up and data collection for the assessment of results.

MARKET TESTS WITH CONSUMER COMPANIES

- Identification of consumer companies of products generated by the transformation technology and who are interested in participating in market tests.

- Adaptation of the products to the company’s processes.
- Follow-up and assessment of test results.

ELABORATION OF AN ECONOMIC VIABILITY STUDY

- Gathering of information on technology and the market.
- Elaboration of an economic viability study for the promising production chains.

DEFINITION OF MARKETING STRATEGY

- Publicizing of success cases.
- Market prospection using appropriate methodology for technological innovation products.
- Assessment of data resulting from prospection.
- Definition of marketing strategy to commercialize the technology.

Conclusions

The knowledge of the production chain of pyrolysis makes it possible to establish the technical and market criteria necessary for the development and implementation of the technology.

PCBT logistics can be divided into three components: raw material logistics, industrial logistics, and commercial logistics of the pyrolysis products.

Raw material logistics is defined by the origin, the environmental restrictions, and the quality of biomass. The knowledge of these factors guarantees the establishment of technical-economical criteria to assess the potential of the raw material.

In industrial logistics, biomass pre-treatment is one of the operations of greatest importance from the technical and economic point of view. In this sense, the standardization process of biomass through torrefaction can contribute significantly to the improvement of the industrial logistics of fast pyrolysis processes by decreasing cost and increasing the processes' efficiency and the quality of pyrolysis products. The new pre-treatment process proposed by the authors intends to create a new concept of biomass called Solid Standardized Biomass (SSB).

Industrial logistics also takes into consideration the pyrolysis process per se. a deep knowledge of the processes and of the technological bottlenecks makes it possible to establish strategies to increase the reliability of pyrolysis technology and therefore reduce logistics costs in the industrial process. This allows for the obtaining of standardized liquid fractions with the intention of introducing new products to the consumer market.

The authors have created the term Liquid Standardized Biomass (LSB) to define a fuel of vegetable origin with constant physical-chemical characteristics that can be offered to the consumer market with guarantees of quality.

Pyrolysis technology presents a Radical level of innovation because it promotes changes in the structure of the existing market and creates a potential for the appearance of new models that will eventually change traditional models. In a broader perspective, it concerns breaking the old paradigm in the concept of technology in the production of bio-fuels. The concept of technology is composed of three aspects: Machine, Knowledge, and Ability to apply knowledge. Therefore the strategy for market insertion must also deal with the implicit knowledge that aims at consolidating the application of pyrolysis products and the skill to put these products in the market. The most appropriate way to reach these goals is through the establishment of a strategic alliance between the players in the production chain (the holder of technology, the producer, and the final consumer). This kind of alliance intends to create a success case in which the risks associated to the market and the technology are reduced and to provide a learning period in which a larger scale consumer market can be consolidated.

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