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Life-Cycle Assessment and Life-Cycle Cost study of Banana *(Musa sapientum)* fiber Biocomposite materials

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Abstract

Biocomposites have a high potential to be ecofriendly and sometimes technically competitive with conventional composites and plastics. Nevertheless, studies are inconclusive about the relative economic and environmental performance of these materials. In this study, biocomposite materials made with banana fiber extracted from Colombian region plantation were evaluated by Life Cycle Assessment and Life Cycle Cost methodologies from cradle to manufacturing. Banana fiber-based composites combinations were compared with polyester resin. The results show the biocomposites alternatives perform globally worse than polyester and are highly dependent of the percentage of resin, type of fiber treatment and to the presence kaolinite.

Keywords: Life-cycle assessment, Life-cycle cost, Biocomposite, Banana natural fiber

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1. Introduction

The use of petrochemical polymers generates environmental damages due to their non-renewable and low biodegradability and their final disposition contribute to the waste landfills and ocean pollution between 22-43% and 6-7%, respectively [1]. The use of fillers of natural fibers (NF) is a sustainable option in composite systems, being included in the realm of biocomposite materials [2]. NF have been used because of their high specific strength, low density, and biodegradability. Moreover, NF are recyclable, non-abrasive, inexpensive, readily available, with low impact on climate change and toxicity for humans [3]. They can be obtained from a number of plants, including flax, hemp, jute, sisal, kenaf, coir, kapok, banana, plantain, henequen, ramie, pineapple leaf, and many others. In some countries, the production of NF benefits millions of farmers. NF are also known as lignocellulosic residues derived from crops, and industrial and agro-industrial processes.

Banana (*Musa sapientum*) and Plantain (*Musa paradisiaca*) are staple food for nearly 400 million people, especially in developing nations. The worldwide exportation of banana was estimated 18.6 million tons in 2014 [4]. Banana/plantain pseudo-stems are mostly cut and disposed at harvesting site. Banana fibers (BF) can be extracted from this underutilized resource. Based on the above-mentioned global production data, million tons per year of BF are potentially available from pseudo-stems. The BF are similar to the current commercialized NF in global market and they could be used in similar applications.

Biocomposite materials in general and the ones based on NF in particular, are potentially eco-friendly materials and their increased use/production are driven by the environmental concerns about the limited resources on earth. Studies dealing with these materials are commonly included among the

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development of sustainable strategies for designing and evaluating of new materials, products, and processes [5]. Some of these strategies are eco-design, life cycle engineering, and green product design [6]. However, most of the studies in this area [7] have focused only in environmental aspects but the development of sustainable products requires a balance between technical, environmental, economic and social aspects.

Life-cycle assessment (LCA) is a methodology commonly applied to assess the environmental effects of the use and processing of materials. LCA studies applied to composites materials showed ecological benefits when using NF and bio-based polymers instead of conventional materials [8]. Nevertheless, in some cases the use of NF does not imply an environment friendly product because the use of pesticides, water and land during the cultivation stage can cause negative impacts [9]. In particular case of BF there are only available publications regarding the mechanical characteristics of the fibers and about the processes to obtain them, so it is very important the application of LCA to assess the environmental impact of these fibers.

Moreover, the fabrication of biocomposite with NF materials might also be an option for achieving the objectives of reducing production costs [10,11]. This alternative may contribute to replace part of the synthetic polymers in engineering applications and commodities in the automotive industry, electronic packaging, aerospace [12]. But again, the economic assessment are still scarce and the analysis through Life Cycle Cost (LCC) performance studies [13] is important to better understand the potential of biocomposite materials use.

The objective of the present study is to evaluate LCA and LCC of four alternatives of BF based biocomposite using unsaturated polyester resin as matrix. The alternatives comprehend different BF treatments and the use, or not, of facilitating agents. The four alternatives are compared with polyester resin using the same component shape and size (tensile test specimen). No finite-element analysis was done to identify the number of layers and fiber percentage required to achieve the same mechanical behavior. So, the technical performance of the alternatives was compared based on the tensile strength measured. In addition, water absorption level was also used to assess technical performance because higher the level lower the composite performance in the use phase. The results of the three dimensions, economic, environmental and technical were integrated in a multi-criteria analysis method. The results obtained from this holistic evaluation, provides important insights about the NF in general and BF in particular. Nevertheless, the study must be further developing to allow more definitive conclusions since the use and disposal phase of the BF composite were not included in this analysis.

2. Methodology

Technical, environmental and economic evaluations were performed from a life cycle perspective, using LCA and LCC, respectively. A global evaluation was done by multi-criteria analysis using the Shannon entropy method [14]. The environmental and economic performance assessment models are briefly described in the following sections. The technical assessment was based on the direct comparison of relevant physical properties of the fibers.

2.1 Environmental evaluation (LCA model)

An attributional LCA study was developed according to the ISO 14040 and 14044 methodology (ISO 14040, 2006; ISO 14044, 2006) by using the Simapro 8.3 software. The methodology for the impact assessment was according to the ReciPe Endpoint (H) method in the three areas Human health, Ecosystems, and Resources.

The present work is a *cradle-to-manufacture* study in order to evaluate the main environmental impacts of including BF in a biocomposite materials. The comparison was carried out of the four alternatives of the table 1 and the polyester resin. A tensile test specimen, a piece of 460 mm × 400 mm × 5 mm size, was the functional unit, prepared according to the procedure described in item 3.1. The system boundaries (Fig. 1) considered the BF conditioning (cut, extraction, wash, and dry) and the biocomposite materials manufacture at laboratory scale (pretreatment of BF and biocomposite materials fabrication). The inventory data related to the fertilizers and land used are not taken into account.

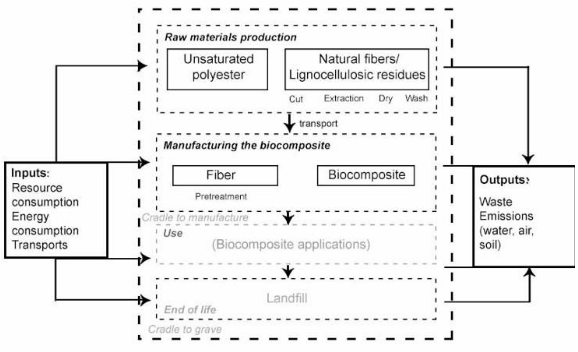

Fig. 1 Biocomposite materials system boundaries

2.2 Economic evaluation (LCC model)

According to AS/NZS 4536:1999 standard, LCC is defined as a process to determine total expenses related with a product (acquisition, installation, operation, maintenance, discarding, and disposal costs) [15]. The first step of the LCC model (Fig. 2) is to gather information from all processes during the entire life cycle stages (raw materials and material processing). After collect this data it is possible to quantify the different cost involved: materials, energy, labour and machine.

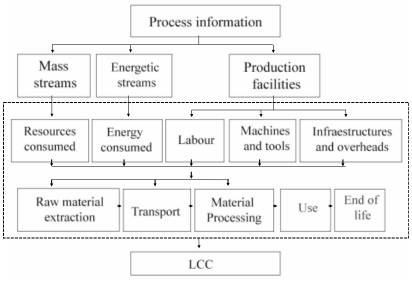

Fig. 2 LCC model

The same data retrieved for the LCA models was used on the LCC model to transform resources consumed and emissions in costs.

2.3 Global evaluation

The multi-criteria decision making (MCDM) is a set of practical methods utilized to find the best alternative among the given criteria. The Shannon entropy is a MCDM method used to find the proper attribute weights for obtaining efficient decisions [14]. In this study, two technical parameters (tensile strength and water absorption), LCA and LCC were included in entropy based MCDM method to compare the four BF based alternatives and polyester resin. The optimization criteria were maximizing the tensile strength and minimizing i) the water absorption, ii) the environmental performance and iii) the economic performance, and then chose the best material option.

3. Results and discussion

This section presents the technical data, the environmental and economic results of the fabricated alternatives and the global evaluation.

3.1 Material

The main parts of banana plants (*Musa sapientum*) comprises fruit (15%), leaves (25%) and pseudo-stem (60%) (also called stem, shoot or stalk). Fresh pseudo-stem (PS) weight per plant is 34-45 kilograms, with an average moisture content of 94-95% [16]. BF were obtained from PS collected from a banana plantation placed in Caicedonia (Valle, Colombia). In this case, there is a cut-off between crop production and biocomposite production, therefore PS contribution in null [17]. After harvesting, the fresh PS were cut, divided and subiocomposite materialsitted to an extraction machine that removes most of the free water content to obtain raw BF. The raw BF were then washed, dried and transported from farms to stocking centers, in this case the laboratory. In the laboratory, the BF are cut by a milling machine and/or woven, for further surface pretreatment and fabrication of the biocomposite materials. The Fig. 3 shows the overall process.

Pretreatment: One of the major drawbacks of BF is its high hydrophilicity that leads to their premature aging, degradation and loss of strength [18]. Therefore, a surface modification (e.g. chemical or physical treatments) is required. The most used chemical treatments are alkalization, silanization, acetylation, and benzoylation [19]. In this study, a chemical treatment was carried out with a blend of epichlorohydrin (EP, 99%) and acetic anhydride (AA, 99%). These reagents were dissolved in acetone (weight ratio, 1:10) and BF were immersed for 24 h at 20°C (reagent to BF weight ratio, 1:5). Reagent residues were removed from BF and reused several times before discarding. Finally, the treated BF were dried in an oven at 105°C for 24 h [20].

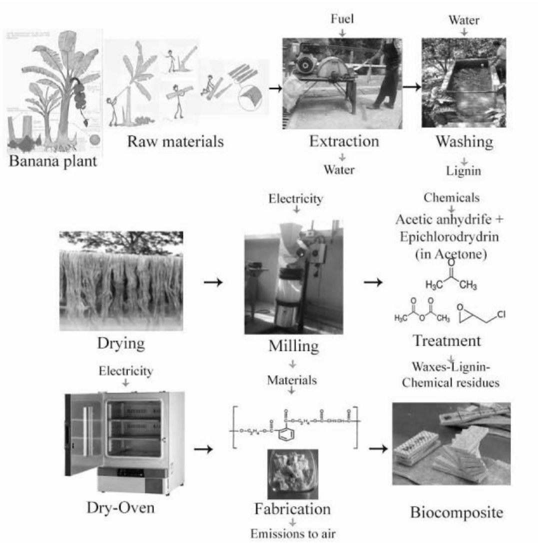

Fig. 3 Process for the fabrication of biocomposite materials with BF.

Preparation of the Composite Specimens: Table 1 shows the different combinations of biocomposite materials. The hand lay-up technique was used to prepare the biocomposite materials pieces with dimensions 460 mm × 400 mm × 5 mm. The cure time was of 24 h at room temperature (21ºC).

Table 1. Combinations of biocomposite materials

Sample	Polyester (%)	BF (%)	AA:EP	Kaolinite (%)
15%BF	85	15	No	0
T:BF	85	15	Yes	0
BF:K	70	15	No	15
T:BF:K	70	15	Yes	15

BF, Banana fiber; T:BF, treated banana fiber; K, kaolinite; AA:EP chemical pretreatment.

The table 2 shows the results of water absorption (ASTM D 570-98) and tensile strength (EN ISO 527-4) of biocomposite materials pieces. The data were taken from previous studies of the authors [20, 21].

Table 2. Water uptake and tensile tests of biocomposite materials.

Sample	Tensile strength (MPa)	Water absorption (8 h) (%)	Ref.
Polyester	15.1	0.80	[22]
15%BF	27.7 ± 2.9	3.95 ± 0.70	[20, 21]
T:BF	30.7 ± 6.2	2.43 ± 0.29	
BF:K	12.4 ± 2.3	1.63 ± 0.11	
T:BF:K	10.5 ± 0.6	0.82 ± 0.15	

Means ± S.D. (*n*=5).

The fabrication of biocomposite materials with BF improved considerably the tensile strength of the unsaturated polyester from 15.1 to 30.7 MPa. Moreover, the inclusion of treated BF and kaolinite significantly reduced the water intake, being the lowest value tested for biocomposite materials (0.82%) comparable with the reported value of polyester (0.80%).

3.2 Environmental Impact Results (LCA)

Fig. 4 depicts the results of the environmental impacts associated to the production of four types of biocomposite materials and the unsaturated polyester resin. Compared to polyester impacts, the biocomposite materials filled with BF and kaolinite (BF:K) and the biocomposite materials filled with treated BF (T:BF) exhibited lower and higher impacts, respectively, for the scope and boundaries considered. The inclusion of biodegradable BF+kaolinite filler reduces the environmental impacts compared to those estimated for petrochemical Polyester and 15%BF sample.

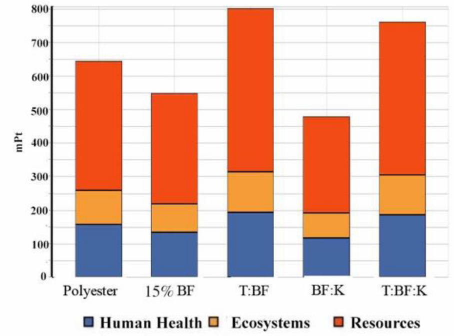

Fig. 4 Comparison of the ReciPe EndPoint H Impacts (mPts/kg product) of the polyester resin and the prepared biocomposite materials samples.

It must be noticed that the use and disposal phase were not considered in this analysis and also the inventory data related to the fertilizers and land used were not taken into account. In the case of hemp and flax studies the fertilizers and land use is one of the main causes of impacts [23]. So, in the BF case it will also have significant influence, but it must be also considered the positive impact of avoiding the disposal of banana trees on crop areas. These stems are currently utilized as green manure but also causing of pests and in other cases are expended as animal feed, incinerated or illegally discharged into the water sources. The analysis of each waste treatment must be included as different waste treatments to define the most appropriate strategy during LCA [24].

Fig. 5 and 6 show the normalization and comparison of the polyester and the different biocomposite materials with the endpoints human health, ecosystem and resources, which is related with weighted damage categories.

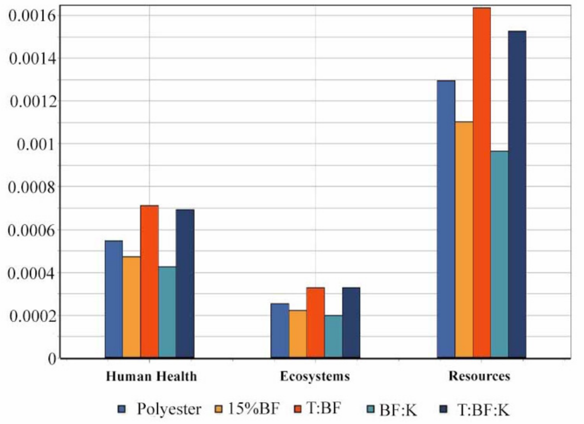

Fig 5 Normalization and comparison of biocomposite materials.

The highest damage would be caused on resources, because of the use of fossil fuel in chemicals and polyester matrix. However, when part of the polyester was substituted by fillers the damage was reduced. In the case on human health damage, the midpoints associated were the climate change, the ozone layer, and the human toxicity. The climate change is caused mainly by those materials with chemical treatment T:NF and T:NF:K. Unlike the ozone layer where the treated BF showed the lowest percentage of impact of all materials, which can contribute to the reduction in UVB-radiation. The damage category ecosystems quality showed lower values for all materials due to their low impact in fresh water and marine ecotoxicity (except of those that use kaolinite).

The percentage of impact contribution of a biocomposite materials of T:BF:K sample is showed in the Fig. 7. This Sankey diagram displays the impact of main components involved in the production of biocomposite materials with

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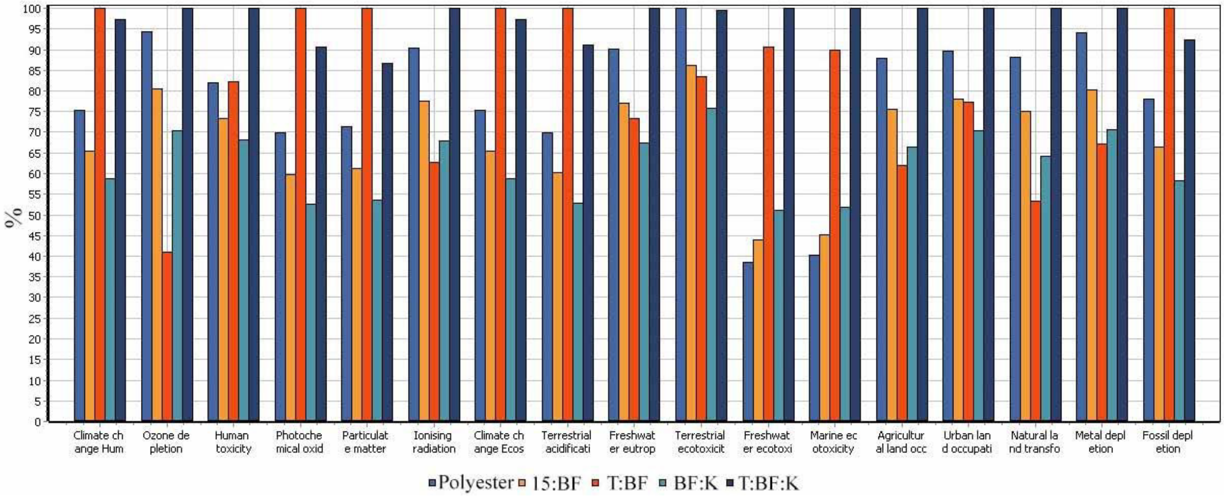

Fig. 6 Contribution of different impact categories with ReCipe Endpoint

treated BF and kaolinite. The major impact is associated to the polyester resin (63.3%) while the impact due to the BF is 36.7% and minimum for kaolinite. The impact associated with treated BF is 16.9% of acetone, 11.3% of AA, and 8.28% of EP 16.9%. Consequently, the overall impact result of the biocomposite materials with treated BF is due to chemical reagents, therefore additional research about alternative surface treatments is required.

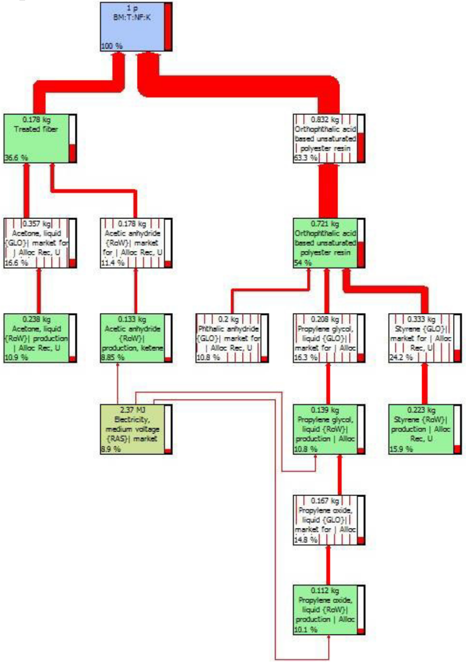

Fig. 7 Percentage of impact contribution by the main components of biocomposite materials (T:BF:K sample) cut-off 8.5%.

3.3 *Economic Results LCC*

Fig. 8 shows the estimated LCC of biocomposite materials production, which are not currently marketed. The costs were divided into four main cost groups: material, energy, labour, and machine. According to the Fig. 3 these costs include for materials: water, reagents (chemicals), kaolinite, and polyester resin; energy: fuel and electricity; labour: calculated according to the hours required and complexity by operation; and machine: shredder, milling, and dry oven. The biocomposite materials with only polyester do not include the costs related to energy and machine, because these costs are for BF extraction.

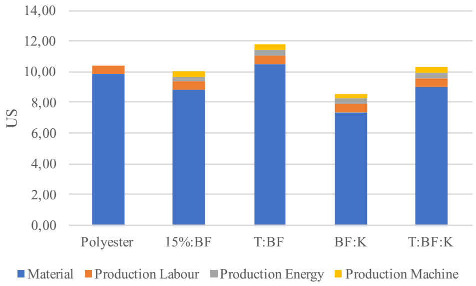

Fig. 8 LCC cradle to manufacturing of biocomposite materials and polyester resin

In this study, the biggest costs are related with the materials. Comparing the cost of polyester with biocomposite materials, the cost is lower for the 15%BF and BF:K alternatives, due to the very low (zero) initial cost of BF (before processing). However, the use of pretreatments to improve the properties of the BF increases its costs significantly, as is the case of the T:BF and T:BF:K alternatives. The best alternative, the one with BF and kaolinite (BF:K), allows a reduction of about 17% of the manufacturing costs of the reference unit. This is a promising result for BF, but it must be notice that this cost is for the same shape size: no study was performed to equalize the mechanical performance by calculating the number of layers of fibers and resin content necessary to level it. So, a global evaluation is performed where besides the economic and environmental performance, the technical performance is also included.

3.4 *Global evaluation*

Finally, the results obtained from the technical, environmental and economic evaluations were integrated to perform the global analysis. Table 3 shows the weighted sum of the four biocomposite materials and polyester resin obtained from the multi-criteria analysis by the method of Shannon entropy. The last line is the weighted by criterion and the last column the results by material. The criterion with the highest weight is the water absorption, followed by LCA, LCC and finally tensile strength. According to the minimizing criteria analysis, the ranking of the materials are: Polyester, following by biocomposite materials with BF:K, T:BF:K, T:BF, and 15%BF. Although the polyester is classified at first option, biocomposite materials with BF:K present a very close score after the integration of the four criteria.

Table 3 Weighted sum of the four MB and polyester resin

	TS	WA	LCC	LCA	
Polyester	0.007	0.029	0.063	0.063	0.162
15%BF	0.004	0.143	0.060	0.053	0.260
T:BF	0.004	0.088	0.070	0.077	0.239
BF:K	0.009	0.058	0.051	0.046	0.164
T:BF:K	0.011	0.030	0.062	0.073	0.175
Weight	0.035	0.349	0.306	0.311	

TS: Tensile Strength; WA: Water absorption

4. Conclusion

In the present study, LCA and LCC studies of biocomposite materials fabricated with unsaturated polyester and BF were presented. By adding two technical performance indicators, a global evaluation was accomplished by using the Shannon entropy method.

In this paper only cradle to manufacturing boundaries were considered. So, the conclusions are limited to this scope and boundaries and further studies are necessary to have a deeper knowledge about the potential of BF as a biocomposites component. Also, the comparison of the biocomposite alternatives with the polyester were based on the same component (a tensile test specimen), so finite elements analysis to estimate the amount of fibers and resin content were not included. The influence of the technical performance of each alternative was included in the global evaluation by using the tensile strength and the water absorption percentage. In this way, the global results express the influence of the different technical performance of each alternative.

The global evaluation show the polyester has a better overall score than the biocomposite alternatives meaning that further research on fiber processing and treatment is necessary to position it as a competitive alternative. Namely, the use of BF in biocomposites materials can avoid its disposal in landfills as occurs nowadays. This might be a positive impact not considered in this study that should be balanced with the fact of pesticides and fertilizers are used in plantation.

Among the biocomposites alternative the alternative with 15% of BF, kaolinite and without chemical pretreatment is better choice because it allows a lower production cost and a lower environmental impact than the remaining ones. Considering the scope and boundaries of the study and the production of the same selected component, this biocomposite has lower cost and environmental impact than polyester, but its lower tensile strength and higher water absorption cause a lower overall performance comparing with the polyester. The other biocomposite alternatives have worst results because of the higher cost and environmental impact of the chemical pretreatment (T:BF and T:BF:K) or because of the very high water absorption percentage (15%BF).

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