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Comparison between sound absorption coefficients of resonant membrane panels laminated bamboo tested in reverberant chamber and virtual simulation

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ABSTRACT

This work reviews the master's research that evaluated the possibilities of using laminated and glued bamboo panels (abbreviated to BaLC) from the species *Dendrocalamus giganteus* in the construction of a resonant membrane material for low frequency sound absorption. The devices were acoustically tested with internal air cavities of 100mm, 75mm, and 50mm thickness with and without glass wool filling. The procedure for obtaining the sound absorption coefficient followed the ISO 354: 2007 international standard with a sample of 12m² of BaLC in a reverberant chamber of 207m3. The results showed the resonance frequency at 100Hz and, consequently, the maximum sound absorption coefficient at the same frequency for all sampling configurations. In the analysis of the sound-absorption coefficients, a variation at 100Hz was observed from 0,387s for empty cavity with 50mm thickness to 0,778s for 50mm cavity filled with glass wool. Furthermore, results were compared with the theoretical prediction in computational modelling to verify if the coefficients obtained in the laboratory coincide with those simulated virtually. This research represents an evidence-based contribution to reveal the benefits of bamboo technology for the built environment given that it can be an accessible resource in tropical countries due to its fast growth and easy adaptation to local soil.

Keywords: architectural acoustics, sound absorption coefficient, resonant membranes, *Dendrocalamus giganteus*, design technologies.

1. INTRODUCTION

The study of unconventional materials for the application in acoustics is relevant, so that there are several researches seeking the acoustic potential of natural fibers and their derivatives, such as sisal, sugarcane bagasse and coconut shells, among others, as well as reuse of components discarded by society, such as tires and pet bottles. In this perspective, the application of materials of plant origin expands the use of these resources and favors the environment, since the uncontrolled and continuous exploitation of the natural resources of the planet generates negative impacts for the human being and environment in which it is inserted (1).

These materials present different acoustic behavior and can be classified as porous or fibrous, for the absorption of high frequencies, resonators, for the absorption of medium frequencies or resonant panels, for absorption of low frequencies (2). Therefore, it is necessary to seek balance in the application of these components in order to obtain a sound control suitable for a particular use. However, the acoustical materials widely available on the market and the verification of their potential for sound treatment are still

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mostly focused on conventional raw materials such as wood and non-renewable resources such as polymers, foams and mineral fibers.

Thus, the possibility of the application of glued laminate bamboo, abbreviated to BaLC, in the form of sheets, similar to plywood, allows its use in architectural acoustics, functioning as a resonant membrane type device that is specialized for the absorption of low frequencies. These systems of sound absorption work by attenuation of sound by mechanical vibration, so they can be designed to absorb certain frequencies, since their maximum absorption occurs at their resonance frequency (3).

Considering the issues presented, this research seeks the introduction of an unconventional material, bamboo as construction material, for application in the sound conditioning in building architecture. The concepts and possibilities of application of this material for the sound absorption will be presented and then the potentialities of absorption will be evaluated, in order to insert the use of bamboo for the acoustic treatment.

2. BAMBOO: NATURAL AND CONSTRUCTIVE CHARACTERISTICS

Bamboo is a material of natural origin and has been prominent as an ally of wood derivatives and other industrialized materials, through the interface that its processing can offer in various uses. It is a plant of tropical origin, perennial and renewable, which annually produces stems and does not need replanting. It is also an excellent carbon absorber, which soon has great potential for the recovery of green areas, as well as the rapid growth of its shoot, which takes from three to six months to reach up to thirty meters (Pereira, BERALDO, 2007).

Its morphological characteristics present analogies with those of wood, suggesting that its acoustic qualities may be similar, however, there are still not many studies about its use for the acoustic treatment of environments. Some researches have shown that the material has desirable characteristics for the development of materials for acoustic conditioning, such as density, fiber size and porosity in its processed product. In this way, the study of acoustics related to bamboo is another important use for this versatile plant.

2.1 Types of Panels

There are several types of panels made from bamboo and are usually processed by a series of chemical and mechanical transformations that involve manufacturing under pressure and suitable temperatures with the aid of adhesives sized according to the bonding capacity of the raw material. Most panels vary from 2mm to 40mm thick, however these conventional dimensions can be altered according to the requirements of the applied use (4).

According to the same author, these panels can be classified according to the technology applied to their manufacture and the type of material processed used in the panel, conforming several different denominations. Moizés (5) concludes that the structural features that will form the final product are directly related to the disposition of slats in these materials, which may have one or more layers with different arrangements in their slats. Figure 01 exemplifies such structural arrangements of the panels.

Therefore, they can be classified as Plybamboo: Bamboo slats are worked at high temperature with the compression and planing of the material, forming plates with thickness between 60mm and 120mm and positioned in the transverse and longitudinal directions alternately. Generally they are hot-pressed and the adhesive based on phenol-formaldehyde is used, however in this type of pressing cracks may occur; and Bamboo glued laminates: The slats are cut and planed with two fixed parallel saws in order to obtain the desired section for use. Then they are arranged in the same direction and glued with a two-dimensional pressing, resulting in a multi-layered product with large possibility. Among the various uses applied to glued laminates of bamboo, the closest thing to this research is plybamboo, that is, the plywood panel of bamboo. Zhang points out that this is a special category in the large variety of bamboo panels, because its main manufacturing characteristic is high-temperature-softening and flattening. A very strong sheet is thus obtained, with high stiffness and wear resistance, whereas its manufacturing process is less labor intensive and consumes less adhesive.

The process of manufacturing this type of bamboo panel involves a series of steps ranging from the collection of the material, followed by steps of slicing of the stalks and glueing of the slats, until the production of its final form. The final product of this process are bamboo plywood panels of various thicknesses and sizes. They are usually glued with three layers perpendicular to each other, however they may be made up of more layers of the material, provided that the opposing faces are aligned with the same fiber direction.

3. RESONANT PANELS

Resonant membranes, also called resonant or vibrating panels, are specialized devices for the acoustic absorption of the low frequencies. According to Bistafa (3) these panels are made of thin sheets of wood or metal fixed to spacers on the walls or ceiling thus constituting a cavity with air inside. According to Gerges (2000), the membrane is an element that does not have sufficient stiffness in a plane, requiring that it be fixed in contours. Thus, if this fixation is made parallel to a rigid plate, the space of air between them will act as an element of rigidity. The operating principle of these panels is based on the excitation of the membrane by the incidence of sound waves at their resonance frequency and, consequently, the dissipation of the acoustic energy by means of the internal damping of the system.

Everest and Pohlmann (6) point out that these panels can be sized to absorb specific frequencies, because absorption of sound waves through the vibration of the system has a peak of absorption that coincides with the resonance frequency of the device, that is, the peak of maximum absorption is the resonant frequency of the system. However, Bies and Hansen (7) note that the determination of the sound absorption coefficient of the system can also be done by an empirical method using forecast plots, published by the Hardwood Plywood Manufacturers Association in 1962, to estimate the behavior of the device. Thus, we first determine the resonance frequency of the system using equation 1, according to Bies and Hansen.

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{\rho c^2}{mL+0{,}6L\sqrt{ab}}}$$

f_0= resonance frequency (Hz);
m = superficial density of the material (kg/m^2);
L = air cavity depth (m); (1)
ρ = specific density of the material, (kg/m^3);
c = sound speed, (m/s);
a = panel width (m);
b = panel lenght (m);

By observing the estimation provided by the equation presented, it can be verified that the thickness of the air layer and the type of material used for the panel are parameters that influence the determination of the resonance frequency of the system. Therefore, reducing the surface mass of the material will cause an increase in the resonant frequency, just as decreasing the thickness of the air layer of the device will also lead to an increase in that frequency.

Further, the air layer of this type of system may also be filled with some porous or fibrous absorbent material, spaced from the panel so that it can also vibrate freely, which will cause a decrease in the system's sound absorption peak and increase absorption at frequencies close to the resonance. Thus, the introduction of these materials into the air layer will decrease the efficiency of the absorption peak sized for the system, but will increase the range of frequencies that the device can absorb (8).

The empirical method to estimate the behavior of the resonant membrane pointed out by Bies and Hansen then uses two parametric graphs that are related to the determination of the desired properties of the sound absorption system. In figure 2, the absorption coefficients for air layers filled with fibrous or porous material, the solid curves from A to F, and for empty air layers, the dashed curves from G to J are shown. On the axis of the ordinates, are shown the coefficient of sound absorption and in the axis of the abscissa the ratio of the frequency band of the frequency of the resonance of the system. Thus, the value of 1.0 on the axis of the abscissa corresponds to the resonance frequency and, therefore, to the sound absorption peak of the resonant membrane. The curves from A to J are estimates of the behavior of the sound absorption coefficients for the frequency bands.

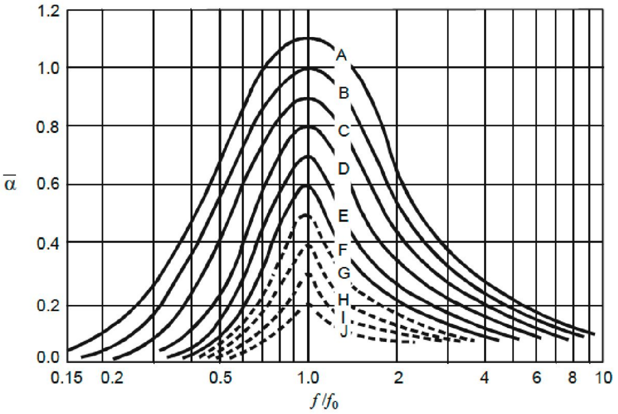

Figure 2 - Prediction curves for the sound absorption coefficient of Sabine.

In figure 3 presents the graph that relates to figure 2 to complement the behavioral estimate of the device. It presents the relations between the surface density of the panel on the axis of the ordinates, and the thickness of the air layer on the axis of the abscissa, the resonance frequency that the system can present on the "f_0" diagonals and the association with the sound absorption curves of figure 2 on the diagonals from A through J.

Therefore, for the behavioral estimation of a resonant membrane type device, the resonance frequency prediction equation must be used in conjunction with the parametric graphs presented to determine the characteristics of the panel, such as its surface density, air cavity thickness and coefficient of sound absorption. According to Bistafa (3) and De Marco (9) it is worth mentioning that the resonant membrane operating principle, a lightweight and flexible panel that will vibrate in its first mode, requires the fixing of its edges in a rigid structure to create a "drum effect" on the membrane. A minimum spacing of 0.4m between the rigid supports is recommended.

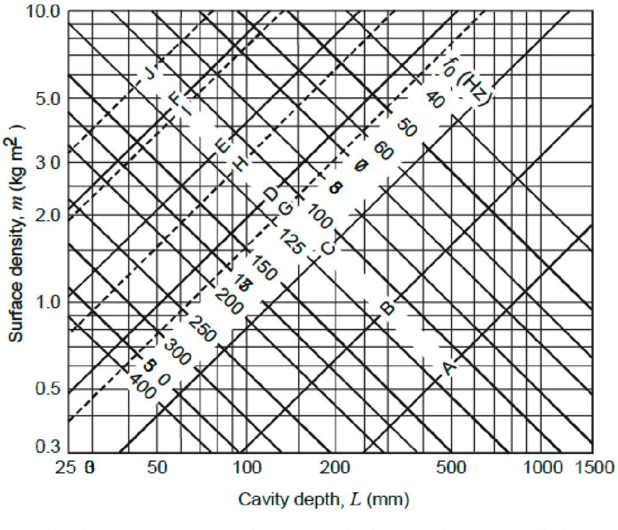

Figure 3 - Prediction curves for the sound absorption coefficient of Sabine.

4. THE PROTOTYPE

For the absorbing system it was projected a membrane consisting of a BaLC panel in only one thickness and an air cavity of variable thickness was designed to be disassembled and reassembled de device. The parts were designed with 4 different layers of air, a bottom membrane, which would confine the air inside the device and a movable pressure frame or frame on the bamboo membrane, to hold the structure and make the components function as a cohesive whole. Thus, there is a system consisting of pressure frame, bamboo membrane, collapsible intermediate rings and bottom membrane.

The thickness of the bamboo membrane was dimensioned based on the width and ideal length produced by the slat slitting machine and the minimum thickness produced by the slat leveling machine. In this way, a slat with a thickness of about 0.2cm, a width of 2.5cm and a length of 120cm is obtained. Also, in order to avoid the deformation by moisture and dilation of the pieces, a membrane of two layers of slats, oriented in a perpendicular way, 105cm long by 105cm wide and 0.4cm thick was designed.

According to Bistafa (3), it is recommended that the minimum distance of the rigid supports from the edges of the resonant membrane is greater than 40cm, in order to allow the plate to work in its first mode of vibration. In order to obtain the resonant frequency variation of the system, it is necessary to modify the layer of confined air inside the device, so the thickness of the bamboo blade was considered a constant and the removable rings change the air cavity. To do so, one can use the behavioral estimation exemplified by Bies and Hansen to define ideal cavity thicknesses based on the constant surface density of the panel. This density was calculated by Oliveira (10) for the material yielded by the CPAB/UnB, obtaining a specific mass of 0.715 g/cm³ and resulting in a surface density of 2.86 kg/m² for the panels, which is the specific mass multiplied by thickness of the panel so as to obtain the density by the area of the panel surface.

However, due to the need for the creation of modular parts that are adapted to the production process, the 75mm cavity, which is close to the resonance frequency of 125Hz and finally modulating the system, was chosen as a final cavity of 25mm which will approach the frequency of 200Hz. Therefore, the air cavities inside the device are defined in 25, 50, 75 and 100mm, and the design of the removable elements is developed.

The removable rings are designed to be easily removed and repositioned. Thus, pieces of 105cm in length, 25mm in width and 25mm in thickness were designed. These pieces together form a frame that supports the bamboo membrane and fit the male-female system so that its connection is firm and prevents the passage of air from the inner chamber to the external environment, confining the air layer inside. It was specified the wood popularly known as freijó (*Cordia goeldiana*) for the construction of the rings, since it is a medium density wood approaching the density of BaLC (11) and is widely available in the market.

The wood popularly known as freijó (or also claraíba, cordia-preta, frei-jorge, among others) is in the phytogeographical domain of Amazonia and can be found in the northern regions, center-west and southeast. It has physical characteristics from moderately hard to manual cross-section, right grain and medium texture. Their vessels are macroscopically visible and have a medium to large diameter and diffuse distribution. It is not included in the endangered species of Brazilian flora and, although it is commonly found in the market, it was not present in the 100 most native species traded in Brazil in 2009. Its main characteristic for this research is its specific basic light mass with value less than 0.50g/cm³.

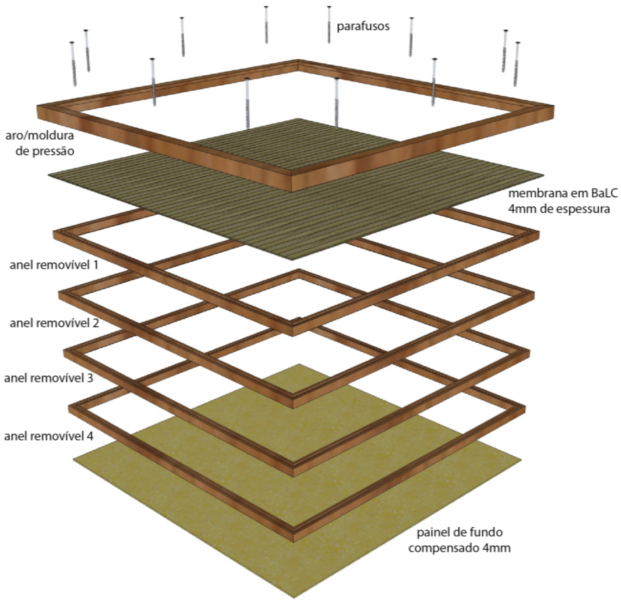

Figure 4 - Exploded view of project component elements separated in order of fit.

For the bottom of the device was proposed the use of wood plywood also with thickness of 0.4cm, length of 105cm and width of 105cm, for the complete sealing of the device. In order for the pressure to be exerted on the parts, bolts with butterfly nuts and washer are inserted which can be easily dismantled by hand. In figure 4 one can be observed a scheme of the functioning of the joints designed for this device.

Thus, we calculated the resonance frequencies for each of the compositions in which the prototype will be assembled and the system behavior was estimated according to Bies and Hansen (2009), based on Equation 01. The 100, 75, 50mm layers had a resonance frequency of 112, 129, 158 and 224Hz respectively.

5. METHODS AND ANALYSIS

For the control of the experiments and also for the classification of each composition in which the air layer is changed, by means of the assembly and disassembly of the removable rings, a specific denomination was created with the following abbreviations: BE100, test of prototypes of the resonant membrane device in BaLC with the internal air cavity 100 mm thick, sealed and empty. The system resonance peak is estimated at 112 Hz; BE075: Assay of the prototypes of the resonant membrane device in BaLC with the internal air cavity of 75mm thickness, sealed and empty. The system resonance peak is estimated at 129 Hz; BE050: Assay of the prototypes of the resonant membrane device in BaLC with the internal air cavity of 50mm thickness, sealed and empty. The system resonance peak is estimated at 158Hz.

In this way, 3 different measurements were obtained in which the air chamber inside the device is sealed and empty, thus a sharp absorption peak was expected at the calculated resonance frequency. However, with the possibility of insertion of porous or fibrous material inside the air box, the following conformations with their abbreviations were also projected: BEL100, Assay of the prototype of the resonant membrane device in BaLC with the internal air cavity of 100mm thickness, sealed and filled with glass wool with a thickness of 50mm. The system resonance peak is estimated at 112 Hz; BEL075: Assay of the prototype of the resonant membrane device in BaLC with the internal air cavity of 75mm thickness, sealed and filled with glass wool with a thickness of 50mm. The system resonance peak is estimated at 129 Hz; BEL050: Assay of the prototype of the resonant membrane device in BaLC with the internal air cavity of 50mm thickness, sealed and filled with glass wool with a thickness of 50mm. The peak resonance of the system is estimated at 112Hz.

The prototypes of the resonant membrane device were tested in the reverberant chamber of UFSM (Santa Maria Federal University) Acoustic Laboratory. This chamber has walls at non-parallel angles whose dimensions range from 7.55 to 7.90m in length, 5.80 to 5.95m in width. The height of this enclosure is also variable, being the smallest dimension of 4.60m and the largest of 4.75m. The measurements total a volume of 207m³ and, still, there are 5 acoustic diffusers of metal suspended by means of chains fixed in the ceiling, contributing to the diffuse acoustic field. It has a double door with acoustic insulation made of sheet metal with 20mm thickness and sealed with rubber. This camera works exclusively for sound absorption tests.

According to ISO 354, test specimens for the reverberation chamber can have various shapes of dimensions, so the method of positioning the sample for the test varies with the type of element to be tested. Absorbent planes or absorbers may be classified as discrete. In this research, the absorbers were considered individual absorption devices, however, they were tested with the positioning of flat absorbers, in this way, they were arranged together forming a rectangle in the center of the room, in proportion as specified in the standard.

For the test, the test area specification varies between 10 and 12m² for a chamber with up to 200m³. If the test environment has a volume greater than that mentioned above, a correction must be made in the test area to be tested. The test sample areas should be between 10.23m² and 12.27m². Also, according to the norm, the discrete absorbers must have at least 1m ² of absorptive area, thus, set of the elements tested fulfilled this requirement, since each prototype had this minimum area of absorption and its set added 12m² of absorber surface.

6. RESULTS

Six sound-absorbing acoustic tests were performed using different voids, filled and empty, for the resonant membrane-type device, but maintaining the same positioning inside the chamber. With the tests, it is intended to evaluate the pre-dimensioning done and to know which of the air thicknesses inside, empty or filled with glass wool, obtained superior performance, for a possible later development of a market product.

Table 1 - Theoretical prediction data of resonance frequency

Test	Cavity	Thickness of air layer (mm)	Theoretical prediction of resonance frequency	Theoretical peak of acoustic absorption coeficient
BE100	empty	100	123	0,6
BE075	empty	75	142	0,4
BE050	empty	50	174	0,4
BEL100	glass wool 50mm	100	123	0,8
BEL075	glass wool 50mm	75	142	0,8
BEL050	glass wool 50mm	50	174	0,6

It was found that the sound absorption coefficients were higher in the bands from 80Hz to 200Hz, for the configurations of the device with the cavity filled with wool of glass. However, the BE075 test, with the empty cavity, showed a very expressive result, as its maximum sound absorption coefficient in the resonance frequency of the system, observed at 100Hz, came close to that of the tests with the filled cavity, according to Figure 81 (P. 126). For all sealed cavity tests, BE100, BE075, BE050, BEL100, BEL075 and BEL050, the resonance frequency of the device was maintained at 100Hz. The highest values for the sound absorption coefficient at said resonance frequency were found in the BEL050 test, followed by the BEL075 and then the BE075.

Table 2 - Tests at reverberation chamber

Coeficiente de absorção sonora por banda de frequência em Sabines (α_s)						
Cavity	Empty			Filled with 50mm glass wool		
Frequência	BE100	BE075	BE050	BEL100	BEL075	BE050
50 Hz	0,056	0,040	0,024	0,055	0,047	0,036
63 Hz	0,119	0,083	0,054	0,122	0,107	0,075
80 Hz	0,268	0,193	0,111	0,407	0,271	0,199
100 Hz	0,566	0,743	0,387	0,671	0,771	0,778
125 Hz	0,348	0,570	0,327	0,359	0,654	0,744
160 Hz	0,142	0,214	0,338	0,335	0,432	0,574
200 Hz	0,266	0,239	0,310	0,362	0,395	0,454
250 Hz	0,227	0,262	0,324	0,231	0,251	0,285
315 Hz	0,166	0,161	0,190	0,187	0,188	0,207
400 Hz	0,179	0,182	0,207	0,159	0,150	0,185
500 Hz	0,142	0,129	0,136	0,136	0,116	0,156
630 Hz	0,134	0,125	0,113	0,131	0,115	0,124
800 Hz	0,123	0,113	0,115	0,119	0,106	0,111
1 kHz	0,108	0,108	0,119	0,106	0,108	0,111
1,25 kHz	0,107	0,106	0,127	0,094	0,108	0,119
1,6 kHz	0,093	0,090	0,118	0,092	0,097	0,113
2 kHz	0,106	0,094	0,115	0,112	0,087	0,102
2,5 kHz	0,123	0,097	0,103	0,115	0,096	0,095
3,15 kHz	0,090	0,090	0,087	0,099	0,081	0,076
4 kHz	0,105	0,084	0,091	0,089	0,085	0,087
5 kHz	0,096	0,088	0,080	0,096	0,088	0,091

7. CONCLUSIONS

The research sought to review the concepts related to acoustics to define the possibility of the use of a nonconventional material for the acoustic conditioning of rooms, the bamboo in its glued laminate form, with the development and experimentation of a prototype that initiated the definition of acoustic characteristics of the proposed material. To that end, the literature reviewed the main properties of sound and its characteristics for room acoustics and acoustic conditioning, as well as the material that was presented to introduce the sound studies.

The experiments showed that the empty cavity of 75mm, in the BE075 test, obtained a maximum sound absorption coefficient close to the highest coefficient found in all the tests, thus demonstrating the capacity of the bamboo membrane allied to the air layer in this system, presented superior performance for the empty cavity, surpassing the calculated estimates. With the 50mm thick glass wool filling in the inner cavity, the BEL050 test, with 50 mm of air layer, presented a satisfactory performance, since it had a high maximum sound absorption coefficient and, compared with the BE050 test, of empty cavity, there was a great variation of absorption in the frequencies of 63 to 250Hz.

The resonance frequencies for each system mounted with the different air thicknesses in its cavity were maintained at 100Hz and differed from those estimated by calculation. This fact demonstrates the need for more acoustic research with the material for the comparison of results and to establish with precision these characteristics obtained in the test.

We suggest an in-depth study on the technical-economic feasibility of an evaluation of the cost and time of production of the material used, taking into account the capacity of the bamboo producers to make their merchandise available; the existing infrastructure for the development of the productive chain; the energy, labor and machinery costs, in order to accurately measure the possibility of marking the panel in BaLC, and its application in acoustics.

Finally, an in-depth study on the positive environmental impacts that the production of acoustic materials in bamboo may entail is also suggested. For, in general, the commercially available materials used for absorption of low frequencies are those derived from wood, such as plywood, OSB and MDF. However, materials for the absorption of high frequencies are derived from non-renewable resources, such as foams and mineral wool. Thus, a comparison between the production of bamboo materials with those available industrial, with respect to the toxicity to the human being, environment and energy required for production, among others, would be pertinent to increase the knowledge of the BaLC.

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