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Article

Use of EPD System for Designing New Building Materials: The Case Study of a Bio-Based Thermal Insulation Panel from the Pineapple Industry By-Product

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Abstract: This study shows the benefits of using the environmental product declarations (EPDs), based on ISO 14025:2013, for the configuration and conceptualization of new building materials. Using a quantitative evaluation on these phases of design, it allows one to create materials with lower impacts, in comparison with the existing ones. In this paper, it is proposed to evaluate the potentiality of this tool in the development of a panel from pineapple by-products from agroindustry, used as a thermal insulator. The issue of environmental sustainability was pursued, employing the assessment of the environmental impacts according to characterization methods defined by the International EPD® System. By comparing the possible compositions of the materials under development, with certified environmental declarations of commercial materials, it is possible to identify and select optimal compositions decreasing up to 98.28% of impacts in acidification potential or up to 99.38% for photochemical oxidation—with respect to traditional materials—already at the design stage, where the changes on the composition or the facilities decision have fewer complications.

Keywords: eco-design; by-products; EPD; industrial resiliency; low-impact materials

1. Introduction

Design is a word widely used in different areas of knowledge to refer to the shape of an object or a drawing [1]. However, the design process goes beyond the object of design; designing is a set of processes that develops since the problem is identified, until a possible solution is achieved [2]. The design is transversal to all areas of knowledge, and the study of its methods solves problems such as the distance between the theory and the object, like the uncertainty in how to declare the environmental impacts [3,4]. For example, in the building industry activities, one of the biggest contributors to climate change, decision-makers have begun to transform their actions into others with less impacts. These changes could be visible on building codes, energy certifications such as LEED or BREEAM, or international agreements, such as the Paris agreement or the Sustainable Development Goals (SDGs) [5,6]. The environmental problems related to designing buildings come from the lack of information and designing methodologies that do not consider quantitative assessments since the early stages of the material's design [6].

The left-hand side of Figure 1 represents the basic 5-step process of qualitative low impact material design; the right-hand side emphasizes the incorporation of the quantitative environmental impact assessments at early stages, as aforementioned.

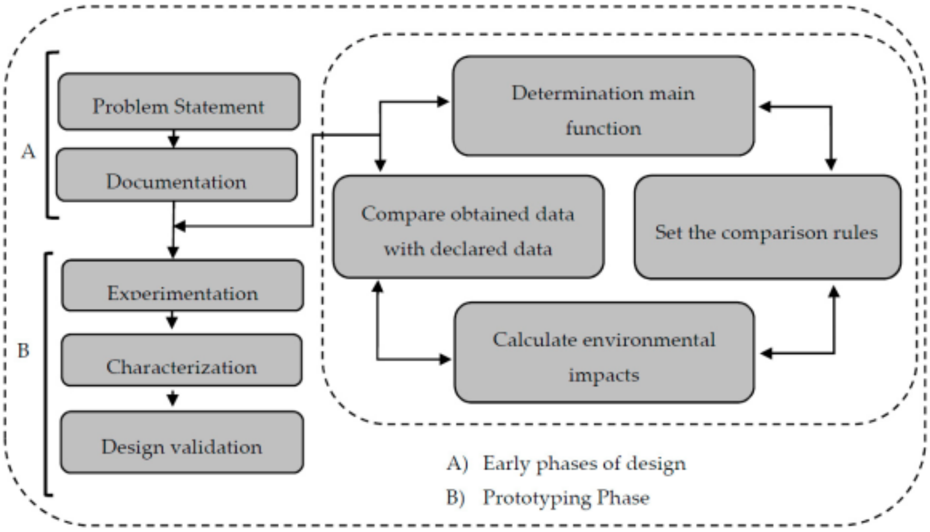

Figure 1. Simple diagram of our methodological proposal for the configuration of low impact materials [2,5].

Designing low impact materials represents an opportunity for the sustainable development of the construction industry. To reduce the environmental impacts, the low impact materials—also called sustainable materials—are based on different combinations of raw materials that may be classified as renewable, biodegradable and/or carbon-negative [7,8]. Materials such as industrial waste, wood, or different clays available on the site have proven in specific cases to be an excellent resource for building, and to allow a reduction in unwanted impacts [9,10].

During recent years, natural fiber-based materials are one of the most utilized "alternative" raw materials for thermal and acoustic insulation purposes. For example, Ali et al. recently developed a thermal insulator composed of two different natural fibers; they proposed six combinations of dried *Eucalyptus globulus* leaves and wheat straw fibers; cornstarch was used as the binder for those composites. They were able to achieve a thermal performance, ranging 0.045–0.055 W/mK for specimens made of eucalyptus leaves only, and values about 0.065 W/mK for hybrid samples, furthermore, the sound absorbing coefficient at frequencies between 500 to 1600 Hz showed values greater than 0.5 for most specimens thermo-gravimetric analysis demonstrated the stability of the composite up to 210 °C [11]. Alabdulkarem et al. [12] reported another natural thermal-acoustic insulator made of palm trees surface fibers and apple of sodom fibers; they used cornstarch, wood adhesive and white cement as the binders for the fibers; thermal conductivity ranging 0.042–0.053 W/mK. Sound absorption coefficient was measured per ISO 10534-2 with the "transfer-function" method [13], showing the potential of using their biocomposite for sound absorption purposes.

It is under these goals that the use of sustainable raw materials is promoted in different parts of the world, where the compromise with sustainable development have more advance or is a priority in the construction practices. Like the European building market, where the reduction on the environmental impacts is more frequently required, as every year the technical building codes become stricter concerning the use of some materials, the energy management and building emissions [14,15]. The sustainable building is also promoted by a new type of certification, granted by institutions such as LEED or BREEAM: they promote buildings where the environmental information, represented in the products, is meant to be scored—the higher the score, the higher the recognition—according to the quantitative measurement of the function and the performance [16].

To achieve this, every year, new materials for the construction industry are developed, with better performance and lower impacts [17]. New building materials that come from by-products of different industries are given a market opportunity; materials as polyethylene terephthalate (PET) residuum bricks, insulation materials made of PET residuum or concrete reinforced by natural fibers of coconut, are only some examples of the new trends on building materials. These materials use resources that have low emissions or come from the landfills, creating a new option with better functional performance, and less energy; that is why resources as natural fibers or by-products improve the environmental behavior in composed materials [18]. The development of materials based on environmental performance needs to become a common practice, not only in one or two main impacts; they need to increase the benefits according to most of the environmental problems currently existing. In some sectors where the offer is extensive, and the industry has a large experience on the function, it is possible to perform different evaluations which allow comparative values, following normative and temporal limits. This is standardized in the life cycle assessment (LCA) methodology, to establish the common units and process, and the interpretation process is simplified [19]. The valid calculation models, standardized units and the procedure are under the ISO 14,044 [20] Environmental management—Life Cycle Assessment—Requirements and guidelines.

This methodology is today the most accepted and trusted one to evaluate the environmental performance of a product [21]. It is important that materials sold as sustainable overcome the theory of the reduction of environmental impacts, through the necessary technical information that supports and quantifies their benefits, with the trustworthiness and the quality to create a reference in the conceptualization of better material. This would certainly support the evolution of the materials in the right direction, solving relevant problems of humankind and its relationship with the environment [22]. The improvement and the diffusion of the life cycle thinking must lead to new methodologies that simplify the declaration and the communication of the environmental performance and its certification. Like the international standard that is creating relevance on this field, ISO 14025:2006 [23] environmental product declarations (EPDs), because it aims to make easier the comparison between solutions, based on a common functional unit and the creation of databases [24]. With this data available, it is possible to define a new scheme to create materials where; since the beginning of the conceptualization, it is possible to evaluate the potential impacts of any configuration, through a standardized report with quantitative values within the boundaries of the LCA. Besides evaluating the environmental problems with priority variables like global warming potential, eutrophication, acidification, ozone depletion, photochemical oxidation, and abiotic depletion, through models recognized by international organizations, it also allows one to recover more information of the production activity [25]. This information also could be integrated to other required information such as costs, using decision support system (DSS), to increase the benefits of use environmental product declarations, and provide more comprehensive information to create policies based on the environmental results and some economic implication, like the limitation on the emissions [9,26].

Through the virtualization of the concept material, it is possible to select the most convenient materials and choose the biological dimension as a target to pursue. For Munari [27], the methodology of design is not absolute and definitive; it is adaptive if the user can find objective values that improve the process, proving that environmental sustainability needs to be added as a main goal for the designing. As mentioned above, it is possible and opportune to use the EPD System, that proposes a standard communication facilitating products selection and promoting communication to the customer, according to the product category rules (PCRs), that include the minimum mandatory information to declare. Each PCR sets a product-related and standardized functional unit and defines the LCA system boundaries to be considered, according to the function of the product: along with the use of specialized software for calculation, PCRs can then enhance the comparability and the reliability of the evaluated environmental impacts. Furthermore, the PCRs are created by decentralized organizations, companies, and some governmental actors for creating more integration among the stakeholders and an increase in their social responsibilities [17,28].

According to aforementioned, this paper shows the advantage of using LCA methodology and life cycle inventory (LCI) in a new way, to design low impact materials, through the conceptualization, based on the environmental product declaration and the comparison between commercial materials. The material considered in the paper is a part of multidisciplinary research conducted within a larger project, mainly focused on the usage of agricultural by-products into a thermal insulating alternative-material, mostly intended for the building industry. Particularly, according to Roshafima et al. [29], pineapple is commonly used as a reinforcement fiber, as its fibrous residues are primarily formed by cellulose, hemicellulose, and lignin: such a composition enables them to be used in the manufacture of pulp, paper, production of alternative fuels and adsorbent, among others [30].

2. Materials and Methods

For the validation of the proposed methodology of design, a bio-based material under development was selected as a case of study to reduce its environmental impacts. This material is part of a project to produce a new insulation material, focused on reducing the environmental impacts related to the non-renewable materials used in the manufacture of other thermal insulators that come from fossil reserves. In our case of study, the materials used for its configuration come from a by-product of the pineapple agroindustry, in combination with commercial clay and some other substances that could produce an adequate performance. Two configurations for the bio-based thermal insulation panel were selected to validate the design methodology; these configurations are described as follows:

(1) A slab made of pineapple by-product and clay with low structural resistance and medium water permeability.
(2) A slab consisting of pineapple by-product, clay, and a PLA biopolymer, with low water permeability and good structural resistance.

The low impact configuration declared in the paper was subsequently tested to evaluate their thermal and mechanical performance. Thermal conductivity values proved to be 0.048 W/mK, this value agrees with the value of other insulation materials [11,12,31]. On the other hand, to analyze the bulk velocity of soundwaves through these materials, we can consider that such velocity can be given by $v = \sqrt{\frac{Y}{\rho}}$, where Y is Young's modulus and ρ the average volume density. Each value was determined as 0.78 GPa, 1.59 GPa for Y, and a common average density of 1.098×10^3 Kg/m^3, obtaining values of 845 m/s and 1206 m/s, respectively. This shows an attenuation of sound through the material compared to other solids [32]. Furthermore, mechanical characterization was performed, following experimental procedures such as the one proposed by Graupner for the measurement of tensile strength [33] and thermal characterization following the ASTM C518-17 Standard Procedure [34]. Another important parameter required to be measured is the sound absorption coefficient at normal incidence [11–13,35,36], which can be described as "*the ratio of sound power entering the surface of the test object to the incident sound power for a plane wave at normal incidence*" [13]—the higher the value of the coefficient, the higher the acoustic insulation performance—some other complimentary characterization such as the moisture content determination and the three-point bending moment test [11] are still pending to be carried out, for further stages of design and characterization in our biocomposite.

For the object of this paper, evaluation by EPD methodology was performed, based on the PCR 2012:01-SUB-PCR-I [37], where the functional unit and the phases stabilized for the LCA comparison of insulation material is listed. The EPD is the best way to communicate the contribution to the most important environmental problems nowadays, and it is used for commercial products in the market. However, its use in a design phase could give the direction to configuration and obtain better environmental performance when the technical decisions do not imply a big economic investment.

First, in the article are listed all the raw materials required for two configurations (Tables 1 and 2), in the units required to produce 1 m^2 of insulation panel for the thickness necessary to provide a 1 K·m^2/W of thermal resistance on international system units (RSI), in accordance with the functional unit defined by the PCR. The components are the result of the early phases of conceptualization and experimentation, and its configuration is easy to change, because it has not scaled to industrial production and its composition is not definitive.

Table 1. Preliminary components of bio-based material, according to one square meter for the thickness necessary to produce 1 K m^2/W.

Components	Mass (Kg)	Proportion
Pineapple By-Product	29.3	26.10%
Tap Water	57.3	51.04%
Fire Clay	23.355	20.80%
Acetic Acid	1.6	1.43%
Wheat Flour	0.71	0.63%
Total	112.265	100.00%

Table 2. Second configuration of bio-based material, according to one square meter for the thickness necessary to produce 1 RSI.

Components	Mass (Kg)	Proportion
Pineapple By-Product	22.424	38.18%
Tap Water	15	25.54%
Polylactic Acid	10.296	17.53%
Fire Clay	7.272	12.38%
Virgin Wax	1.376	2.34%
Glycerin	1.212	2.06%
Acetic Acid	0.357	0.61%
Wheat Flour	0.16	0.27%
Yucca	0.64	1.09%
Total	58.737	100.00%

To understand the conceptualization of this material, the components were selected by a theoretical sustainable performance. In other words, its physical properties were selected to reduce the energy demand for its transformation, its reserves on the planet being high and renewable, or being a recycled material. Three of these components represent 97.94% of all the gross mass. First of all, the pineapple peel is reincorporated from the industrial process of pineapple: being a by-product, this component is considered as zero-impact, since the commercial products are responsible for all the impacts derived from their production, according to the Polluter Pays Principle (PPP) [38]. Secondly, clay is an abundant and natural raw material potentially available on different parts in the world, easy to extract from the ground, requires very little energy processing once excavated and it could be reintegrated to the earth with minimal secondary effects. Thirdly, water is an abiotic resource, which in the drying process of the material, it is mostly reintegrated by evaporation into its natural cycle [39]. This logical thinking is common in some theories of eco-design, and it is the common justification of sustainability applied to the development of new materials [40].

Secondly, with the characterization of preliminary materials, it is possible to create a model able to evaluate its potential environmental performance. The evaluation model listed in the PCR selected is the sub-category (version 2.3) "Thermal insulation products" elaborated by the International EPD System, valid for the building materials [37]. The LCA boundaries refer to cradle-to-gate with options (Table 3). For the evaluation, only the upstream and core phases will be calculated, because the downstream phase is under development. Nevertheless, only these phases are mandatory in the PCR, and many commercial products with EPD certificated have only listed these phases. Furthermore, the material has biodegradable qualities, that in the future evaluation, could give fewer impacts in the recovery phase.

Table 3. Boundaries as given in the LCA methodology [37].

Life Cycle Stages in the International EPD® System	Asset Life Cycle Stages (EN 15804)	Information Module (EN 15804)	Declared Unit: Cradle-Gate, Cradle-Gate with Options
Upstream	A1) Raw material supply	A1–A3) Product stage	Mandatory
Core	A2) Transport		
	A3) Manufacturing		
Downstream	A5) Construction installation	A4–A5) Construction process stage	Optional for an product and mandatory for a service
Other Environmental Information	D) Future, reuse, recycling, or energy recovery potentials	D) Recovery stage	Optional

Data Collection

In the next step, the allocation of the impacts that come from raw materials and its transportation was collected from different data sources, that could comply with the information required in the calculation (next part) and registered in the Tables 4 and 5. The lack of data about the local production on the Mexican market is solved by some scientific literature, LCA reports, LCI databases, such as Ecoinvent 3.4 [41], Agri-footprint 4.0 [42], and USLCI [43], or information published by the producers on the requirements of labeling of the country, to give reference to some elements in the final calculation [44].

Table 4. LCA data source and origin of the first configuration of the material.

Raw Material	LCA Data Source	Origin
Pineapple By-Product	Polluter Pays Principle (PPP) [45].	The pineapple by-product comes from a natural fruit of the family of *Bromeliaceae* species, *Ananas comosus*, originating in the tropical zones of Brazil. This is cultivated in Veracruz, Mexico, in the zone of Papaloapan, where the company's supplier facilities are placed. The company is dedicated to the production of juices and conserves, due to the quality controls on the production, the by-product is almost standardized from the entrance of the supply chain [46].
Tap Water	LCI	Water comes from the tap, through the Mexican National System of distribution of National Water Commission [47].
Fire Clay, From Clay Ball	LCI	The clay is a commercially available product that comes from Kentucky, United States; it is collected from river rocks, where it is mechanically ground and dried before commercialization [48].
Wheat Flour	LCI	Wheat flour comes from a commercial product processed in a local company where the product is developed; it is distributed in packages of one kg of kraft paper [49].
Acetic Acid	LCI	Acetic acid glacial comes from a chemical industry in Mexico City where it is commercialized in bottles of polypropylene of one liter [50,51].

Table 5. LCA data source and origin of the materials added or changed on the second configuration.

Raw Material	LCA Data Source	Origin
Polylactic Acid	LCA Report	This bio plastic comes from plants as corn, cassava, sugar cane or beets and are transformed into long-chain sugar molecules. Besides a process of milling, hydrolysis, and polymerizing, microorganisms transform the lactic acid into polylactic acid [52].
Fire Clay	LCI	The clay is a commercially available product that comes from Teximalpa, Veracruz, Mexico. It is collected from rocks, it is mechanically ground and dried before commercialization [53].
Virgin Wax	PPP	Comes from an apiarium in the same city. This is a by-product of the production of honey and the process of extraction only uses solar energy, and physical process for filtering the impurities. This is a commercial product that is sold by bulk in kg.
Glycerin	LCI	This product comes from vegetable sources and is processed in a company in Mexico City. Where it is commercialized in bottles of polypropylene of 4 L [54].
Cassava	LCI	Cassava starch comes from Cassava that is cultivated in the State of Guerrero Mexico and distributed at a local market of Toluca.

For transportation, the distance between place of distribution and facilities place, were calculated using the fastest route given by the Mexican road system applied to the transport way used or declared by the seller (Tables 6 and 7).

Table 6. Distance between the facilities place of first configuration components and the raw materials place of production.

Raw Material	Place of Distribution	Type of Transportation	Distance to Facilities Place
Pineapple By-Product	Papaloapan, Veracruz, Mexico	Lorry diesel 2 tons	550 km
Tap Water	Toluca, State of Mexico	TAP	10 km
Fire Clay	Kentucky, US	Diesel train, lorry diesel 36 tons, lorry diesel 2 tons	2500 km, 69.6 km, 7 km
Wheat Flour	Toluca, State of Mexico	Lorry diesel 2 tons	20 km
Acetic Acid	Mexico City	Lorry diesel 2 tons	83.3 km

Table 7. Distance between the facilities place of the second configuration and the raw materials place of production.

Raw Material	Place of Distribution	Type of Transportation	Distance to Facilities Place
Polylactic Acid	Blair, Nebraska, United States	Diesel train, lorry diesel 36 tons, lorry diesel 2 tons	2830 km, 54 km, 12 km
Fire Clay	Teximalpa, Veracruz, Mexico	Lorry diesel 36 tons, lorry diesel 2 tons	220 km, 56 km
Virgin Wax	Cacalomacan, Toluca, State of Mexico	Lorry diesel 2 tons	40 km
Glycerin	Atizapan, State of Mexico	Lorry diesel 2 tons	98.8 km
Yucca	Jungapeo, Michoacan, Mexico	Lorry diesel 2 tons	120 km

The energy required for the process of transformation reported in Tables 8 and 9 comes from the national electricity mix, PEMEX production of liquefied petroleum gas (LPG) and solar radiation.

Table 8. Energy required on the first configuration, according to one square meter for the thickness necessary for producing 1 K m^2/W [41].

SOURCE	ELECTRICITY	HEATING	LCA DATA SOURCE
MEXICAN MIX	0.014 kwh		LCI
GAS L.P., PEMEX MIX.		814.148 Kcal	LCI

Table 9. Energy required on second configuration, according to one square meter for the thickness necessary for producing 1 K m^2/W [41].

Source	Electricity	Heating	LCA Data Source
Mexican mix	0.012 kwh		LCI
Gas l.p., Pemex mix.		706.148 Kcal	LCI

The package residuum of the manufacturing process goes directly to the landfills and the drainage local system, whereas the water used is partially collected by the drainage system and the rest evaporates during the drying process and goes directly to the air. The quantity of residuum is referred to as the functional unit and reported in Tables 10 and 11.

Table 10. Residuum quantity of first configuration, according to one square meter for the thickness necessary to produce 1 K m^2/W.

Components	Mass (kg)	Proportion
Water, disposal to the air	36.2	50.41%
Water with particles of pineapple peel disposal to the drainage local system	31.97	44.52%
Kraft paper	2.7	3.76%
Polypropylene	0.944	1.31%
TOTAL	71.814	100.00%

Table 11. Residuum quantity of second configuration, according to one square meter for the thickness necessary to produce 1 K m^2/W.

Components	Mass (kg)	Proportion
Water disposal to the air	5	36.80%
Water with particles of pineapple peel disposal to the drainage system	7.648	56.28%
Polyethylene	0.21	1.55%
Kraft paper	0.663	4.88%
Polypropylene	0.067	0.49%
TOTAL	13.588	100.00%

3. Results and Discussion

The evaluation of the environmental impacts was performed with SimaPro®, using some of the characterization methods provided by the EPD 2013 [28], are shown in Table 12. The EPD 2013 models the results listed in the data collection and results and discussion section, with the rest of the information required, transportation, energy, and the residuum of the transformation.

Table 12. Results of calculation, EPD 2013 Model [55].

Impact Category	Unit	EPD 2013 Results of a First Configuration	EPD 2013 Results of a Second Configuration
Acidification (fate not incl.)	kg SO_2eq	0.0934	0.33
Eutrophication	kg PO_4eq	0.0253	0.0508
Global warming (GWP100a)	kg CO_2eq	15.8	42
Photochemical oxidation	kg C_2H_4eq	0.0026	0.0137
Ozone layer depletion (ODP) (optional)	kg CFC–11 eq	2.1×10^{-6}	2.14×10^{-6}
Abiotic depletion (optional)	kg Sb eq	5.6×10^{-5}	31.7×10^{-5}
Abiotic depletion, fossil fuels (opt.)	MJ	210	551

3.1. Comparison between Configurations

The comparative analysis between the two listed configurations of biobased materials shows that the first composition had a considerable decrease in the environmental impacts, assessed by the EPD (Table 12 and Figure 2). This first configuration, which is mainly composed of clay and pineapple by-products, has a better performance than the second one where PLA was added. PLA material has 71.7% of the acidification impacts, 50.2% of eutrophication impacts, 62.4% of the global warming potential impacts, 81% of photochemical oxidation impacts, 82.3% of the abiotic depletion impacts and 61.9% of the abiotic depletion of fossil fuels impacts. Hence, it is one of the highest contributors as a raw material in the environmental impacts at this designing stage (Table 13).

PLA is a biopolymer frequently used in the 3D printing and food industry, since it comes from renewable sources and it is biodegradable in a short period of time, in comparison with fossil origin polymers. However, the granulation process of PLA is still energy-demanding, and its impacts affect all the impact assessment categories. It is important to understand that the production of PLA is independent of this system, so a cleaner production of PLA could reduce the account in all sub-systems, but for now, it is only a possibility.

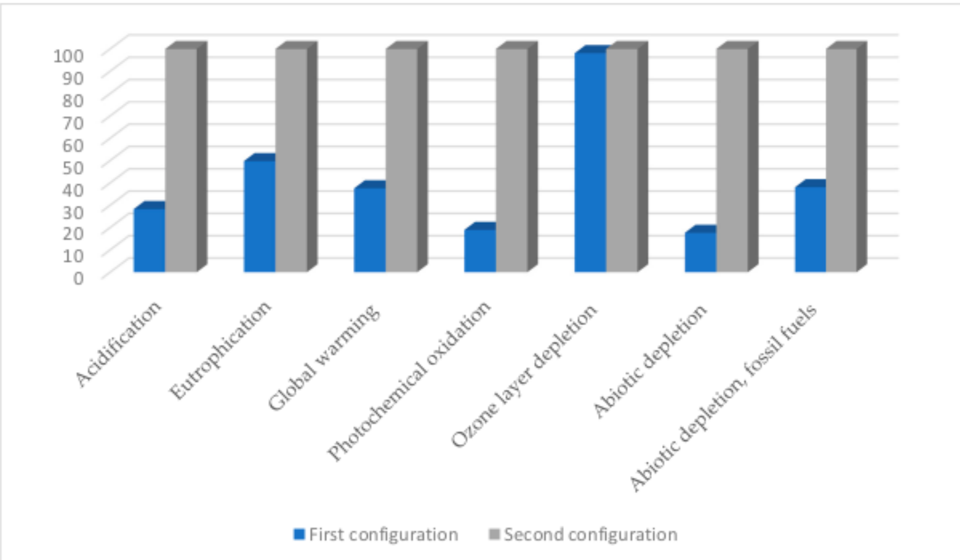

Figure 2. Percentage of impact between the two configurations.

Table 13. Material and transportation with the highest impacts in both configurations, EPD 2013 Model [55].

Impact Category	Fire Clay Used in the First Configuration {GLO}	Transport, Fire Clay {US}	Polylactide Acid, Granulate Used in the Second Configuration {GLO}	Transport, Polylactide Acid {US}
Acidification (fate not incl.)	25.4×10^{-3}	12.27×10^{-3}	0.232	7.83×10^{-3}
Eutrophication	8.4×10^{-3}	2.22×10^{-3}	16.1×10^{-3}	1.41×10^{-3}
Global warming (GWP100a)	5.36	1.098	25.4	0.596
Photochemical oxidation	1.1×10^{-3}	-5.77×10^{-5}	11.2×10^{-3}	-8.44×10^{-5}
Ozone layer depletion (ODP) (optional)	5.4×10^{-7}	5.06×10^{-8}	9.25×10^{-11}	2.66×10^{-9}
Abiotic depletion (optional)	1.43×10^{-5}	7.61×10^{-7}	5.05×10^{-5}	4.42×10^{-8}
Abiotic depletion, fossil fuels (opt.)	61.2	15.63	356	8.369

By contrast, the first configuration that does not include PLA, also has some changes in its composition because of the evaluation. For example, clay is available in most parts of the world, it is one of the best components in the building market, not only because it has been used in ancient buildings, but also for its benefits at the end of the cycle. When comparing the environmental impact of the two clays used in our design, one of the relevant differences comes from the distributor-user separation; the first configuration used clay coming from Kentucky, U.S. and the second from Veracruz, Mexico. Otherwise, the change of the product transportation could lead to a significant reduction of the emissions. The use of cleaner systems is always the desirable option, although it is highly dependent to the availability of the technology in the place. For example, in Mexico, product transportation is mostly made by lorry; it works with fossil fuels, leading to an increase of the environmental impacts. Lorry and car are the most usual options for transportation, due to the large infrastructure available in the country.

The use of agricultural by-products, such as straw and other natural fibers are very suitable in combination with clay for achieving excellent comfort properties in a construction material. Most of the natural fibers are products that have low impacts regarding transformation and extraction processes [56]. They present high thermal inertia, which allows them to store heat and to regulate the temperature changes between day and night; this behavior is possible due to the porosity and the air that is contained in the fibers [57].

The use of by-products is promoted by different international and local agreements; for instance, SDGs or the National Strategy for Sustainable Production and Consumption in Mexico; as well as in different theories like the circular economy, where the design determines 80% of the environmental impacts and benefits of products [6,56,58,59] and PPP [45].

3.2. *Comparison between Best Configuration of the Material Proposed and Commercial Materials*

Moreover, the comparison between materials with the same function is necessary to give a reference for the levels of sustainability. To achieve that, the results should be compared with other commercial products used for the same functional use, which is also EPD certificated and published in the international EPD system [23,28] (Tables 14 and 15).

Table 14. Comparison of the results between the insulation materials with EPD in the international System, part one.

Impact Category	Unit	MAPEI® Mapetherm EPS [60].	Aspen® Spaceloft® Aerogel Board [61].	First Configuration of Biocomposite Insulation of Pineapple By-Product	Roland® Rockwool Insulation Board [62].	ANIQ® Expandable Polystyrene EPS Insulation Board [63].
Acidification (fate not incl.)	kg SO_2eq	0.0337	0.0603	0.0934	0.0055	0.0292
Eutrophication	kg PO_4eq	3.80×10^{-3}	6.20×10^{-3}	2.53×10^{-2}	7.0×10^{-3}	4.4×10^{-3}
Global Warming (GWP100a)	kg CO_2eq	10.7	10.25	15.8	6.5961	5.353
PhotocheMical Oxidation	kg C_2H_4eq	3.06×10^{-2}	4.16×10^{-3}	2.6×10^{-3}	3.2×10^{-3}	2×10^{-3}
Ozone Layer Depletion (ODP)	kg CFC − 11 eq	1.23×10^{-6}	3.42×10^{-6}	2.1×10^{-6}	0	3.06×10^{-7}
Abiotic Depletion	kg Sb eq	6.29×10^{-3}	4.89×10^{-5}	5.6×10^{-5}	6.85×10^{-2}	4.89×10^{-2}
Abiotic Depletion, Fossil Fuels	MJ	220	91.6	210	124.54	90.3679

Table 15. Comparation results between the insulation materials with EPD in the international System, part two.

Impact Category	Unit	ODE ISIPAN® Extruded Polystyrene (XPS) [64].	REXPOL® Cappotto White, EPS 100 [65].	FREUDENBERG® Polyester Insulation Nonwoven Panel [66].	ODE® STARFLEX 042 Glass Wool [67].	ISOVER® Glass Wool Insulation 4+, without Facing [68].
Acidification (fate not incl.)	kg SO_2eq	0.0173	0.0044	5.444	0.0006	0.0045
Eutrophication	kg PO_4eq	8.60 × 10−3	1.40×10^{-3}	2.212	1.70×10^{-3}	1.40×10^{-3}
Global warming (GWP100a)	kg CO_2eq	4.327	2.332	2.008	0.9903	0.7973
Photochemical Oxidation	kg C_2H_4eq	1.108×10^{-3}	1.589×10^{-2}	4.23×10^{-1}	2.8307×10^{-4}	2.9089×10^{-3}
Ozone Layer Depletion (ODP)	kg CFC − 11 eq	1.1585×10^{-7}	9.205×10^{-8}	0	6.4408×10^{-8}	1.0859×10^{-7}
Abiotic Depletion	kg Sb eq	3.6291×10^{-6}	0.5732×10^{-6}	0	0.2850×10^{-6}	1.7825×10^{-6}
Abiotic Depletion, Fossil Fuels	MJ	84.207	55.463	52.096	17.5008	13.0769

As the final part of the study, Tables 14 and 15 show the EPD results calculation, as well as the results declared by nine insulation materials in the international EPD system. From the same Tables, it can be observed that, even when one impact category is zero, the others may not be neglected; therefore, all materials contribute to the global environmental problems in different ways. Although our proposal leads to some impact assessment categories' higher values than the reported by commercially available materials listed in Tables 14 and 15, one should pay attention to the fact that, even when there are more insulation materials on the market, these are the only ones with environmental impact declarations up to 2019.

When comparing the materials with highest and lowest impact category values in a graphical manner, Figures 3 and 4 were obtained. In this case, the highest impacts material with an environmental product declaration issued in 2019 is FREUDENBERG® polyester insulation nonwoven panel [66], and the materials with the lowest impacts with environmental product declaration available in 2019 are ODE® STARFLEX 042 Glasswool and ISOVER® Glass Wool Insulation 4+ [67,68]. In this case, both materials were selected because they have low average impacts.

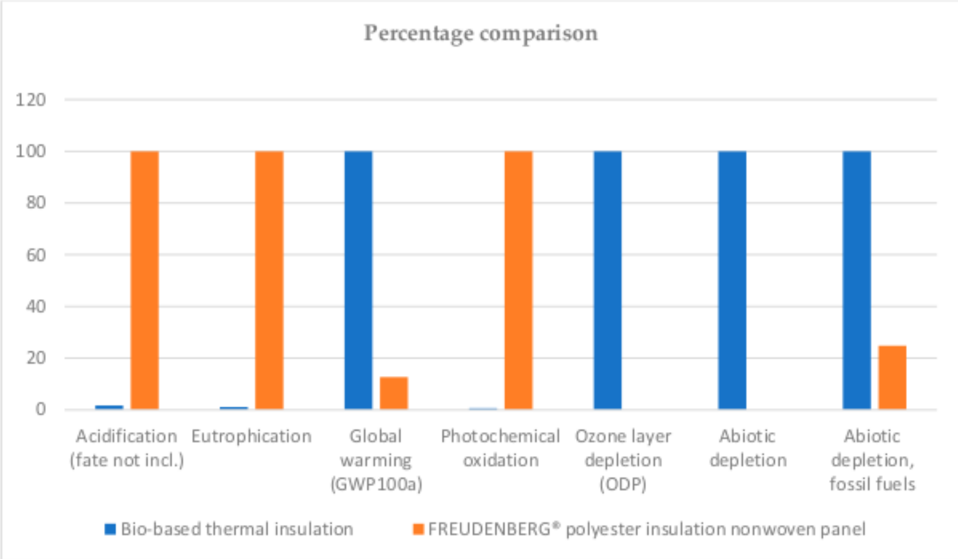

Figure 3. Percentual comparison of impacts between bio-based material and the material with the highest impacts with EPD available.

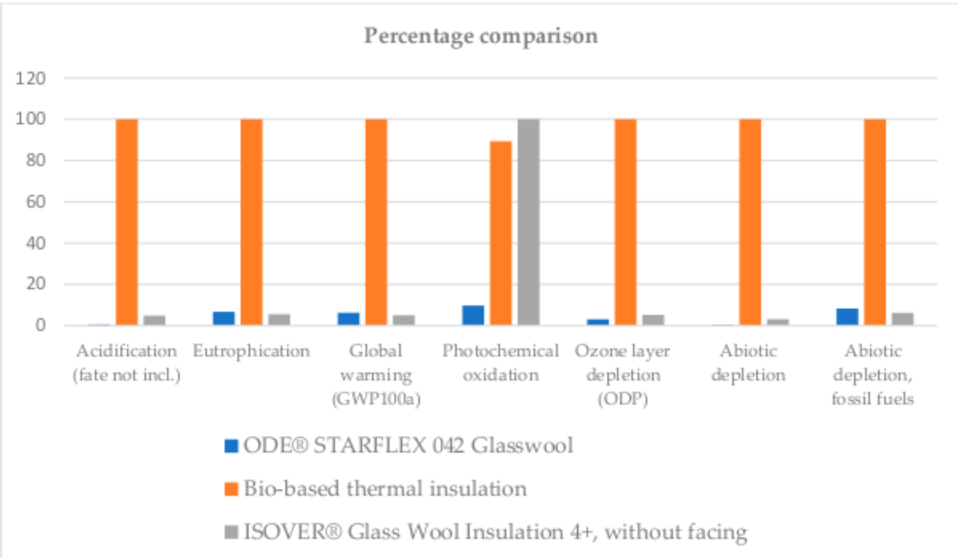

Figure 4. Percentage comparison of impacts between bio-based material and two materials with the lowest impacts with EPD available.

Even when the material proposed in this paper, compared with FREUDENBERG® polyester insulation nonwoven panel [66], has 87.3% more global warming potential impact, 87.3% more ozone depletion impact, 99.99% more abiotic depletion impact and 75.2% more abiotic depletion fossil fuels impact, it has 98.28% less acidification impact, 98.86% less eutrophication impact, and 99.38% less photochemical oxidation impact. On the other hand, when compared with ODE® STARFLEX 042 Glasswool [67] and ISOVER® Glass Wool Insulation 4+ [68] only photochemical oxidation of ISOVER® Glass Wool Insulation 4+ [67] has 10.7% more impact.

These results show than the pineapple by-product panel is one of the thermal insulations with the highest impacts in some categories, in comparison with the materials that have declared their environmental impacts under the model EPD. However, the pineapple by-product panel has additional areas of improvement, which can be systematically achieved, since it is still in the development stage, hence the change on its configuration represents a short and easy decision; another advantage is that the manufacturing location can be adapted to reduce impacts due to transportation.

Due to these integral analyses, it is strongly recommended to include the EPD model calculations before the prototype stage in the designing method. More precisely, between the documentation and experimental steps, showed in a general procedure in Figure 1. This will guarantee a valid comparison of environmental impact categories among in-process products and other(s) that are commercially available.

The common design methodologies of materials are manly focused on the improvement or modification of certain characteristics or properties of a new or modified material; the environmental impacts are commonly taken into account at the last stages of "traditional" materials-design process. Their impacts are calculated when a large amount of resources have been invested in laboratory work to achieve target properties; our proposal to incorporate the EPD calculations during the design stage, could lead to a systematic, efficient and effective optimized integral design process.

4. Conclusions

The advantage of using quantitative methodologies in the evaluation of materials was proven in many cases of the use of EPD and showed in the results of this article. The quantitative data gives a reference for the performance of both configurations, and allows one to select the best one for better environmental performance. Since the design is at early stages, it is feasible to have large possible combinations for the material compositions, which could be possible to adapt under new environmental requirements in a short time during prototype stages. These changes are only subject to calculation, and substitution, also with less or without experimentation. With this information on early phases of configuration, it is possible to improve the environmental performance of production before the manufacturing infrastructure already exists; this can contribute to a better decision making regarding equipment acquisition and manufacturing process implementation in the planning stage, instead of in the operation stage, when the changes are more difficult, and the costs higher. Furthermore, with this information, it is easy to make decisions about the facilities' location or select of suppliers more carefully and push all the markets to introduce sustainable and low impact production.

The best performance of this bio-based material is the result of the first configuration, but some of its raw materials could be exchanged for lower impact materials used in the second configuration, like the clay with lower transportation bearing. Additionally, the use of by-products represents a big opportunity to incorporate on a circular economy, bringing back material that goes to the landfills, where the problem of its management is complicated. The raw materials listed in the table could reduce their impacts if alternative transportation ways are considered e.g., electric mobility.

This alternative design methodology brings new possibilities to other products: with more information, improved products could be created, and will have more opportunities to be accepted in the markets. With the collaborative design based on environmental common information like LCI, it is possible to develop virtual concepts materials that explore different configurations, to improve and optimize the final one before starting the industrial production. This approach may also avoid unnecessary laboratory proofs and processes, that in the end, could result in not reducing the environmental impacts as expected. The calculation according to the IES only requires information, but the information is only possible if the producers collaborate with the creation of the databases. It is strongly recommended to promote the implementation of process-sensing and data analytics in building industry suppliers facilities, in order to reduce the uncertainty linked to the manufacturing process, and to increase the reliability of calculations regarding the environmental performance of products and services.

The EPD model calculation is a more feasible tool for the sustainability assessment that other methodologies focused on qualitative assessments or single index methodologies, like carbon footprint. On the other hand, it is important to address a sustainability index through all the data concerning with the material performance through monitoring the variability of the product dynamics, using sensors within a digital control environment, by means of Fisher's information analysis [69–71].

In the case of the study analyzed herein, thermal isolation performance is quite similar with other natural fiber biocomposites [11,12], but it is remarkable that some additional characterization, as for example the sound absorption coefficient at normal incidence, moisture content determination and the three-point bending moment test are required to be conducted to ensure the suitability of our proposal as thermal-acoustic insulator purposes.

For future considerations, according to the EPD methodology, in addition to the material properties, it is crucial to incorporate it in an adequate shape for a low impact performance, namely, by combining a bio-inspired geometric design, it is possible to take advantage of driving the flows as occurs in a previous panel design [72], where we demonstrate a good performance of thermal insulation in the system, with minimal dissipation.

The use of by-products is promoted by different international and local agreements; for instance, SDGs or the National Strategy for Sustainable Production and Consumption in Mexico; as well as in different theories, like the circular economy, where the design determines 80% of the environmental impacts and benefits of products [6,56,58,59] and PPP [45].

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