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Comparative study into the environmental impact of traditional clay bricks and mixed with a biological ingredient using life cycle analysis

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Abstract: The construction industry is responsible for 40 to 45% of primary energy consumption in Europe alone. Therefore, it is essential to find new materials with a lower environmental impact in order to attain sustainable housing. This study aims to determine and compare the environmental impact of two clay samples forming a basis for the manufacture of traditional brick, a standard material in building construction; traditional red clay brick and a brick based on clay mixed with a biological ingredient. The samples of fired clay were manufactured at the laboratory scale, the results being valid exclusively as indicators for the extrapolation of the analysis to other studies. The results of the environmental impact of these formulations have been examined through an evaluation of life-cycle analysis (LCA), observing that the incorporation of biological pore forming agents led to a decrease of around 15 to 20% of all impact categories studied. Thus, the suitability of using biological-based additives in clay bricks was confirmed both for their constructive characteristics (lighter material) and increased energy efficiency (better thermal insulation) considering the environmental point of view.

Keywords: Life-cycle analysis (LCA); sustainable materials; sustainability climate impact; bioclimatic architecture; green buildings

1. Introduction

Building and road construction is responsible for almost half of the raw materials and energy consumed throughout the planet [1]. Consequently, construction has a great impact on the depletion of finite resources in addition to greenhouse gas emissions resulting from the combustion of fossil fuels. In order to reduce the associated greenhouse gas emissions and resulting impact on the climate, it is necessary to use environmentally sustainable building materials [2] [3].

Clay bricks have been widely used for thousands of years in the construction of houses, since it is an economical product which uses cheap raw materials (clay, sand and water) and a simple process of manufacture, firing. However, since their arrival in the 1980s and due to construction systems based on exterior enclosures of concrete blocks, the market for clay-based bricks began to decrease. Nevertheless, the producers found technological barriers due to the limitation as insulating objects, in addition to which their weight limits their use to low height buildings [4] [5].

Nowadays, in the context of sustainable development and with thermal regulations, it is necessary to develop new construction materials with high thermal and mechanical performance.

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The incorporation of by-product or waste from different origins has been evaluated to improve these properties. [6].

Historically, there are studies that apply LCA, to the materials used for the construction of buildings since the 70s, especially in Germany [7-9]. Thus, life cycle analyses have been carried out in residential sectors such as houses [10], or single-family homes [11], to establish strategies for reducing gas emissions in residential sectors through new construction structures in hot and humid conditions [12].

Following these guidelines, studies are being carried out in the United Kingdom applied to LCA that demonstrate that materials of biological origin such as hemp, introduced in the manufacture of construction materials, improve the environmental impact. Hemp is a natural resource that has recently been used as a low environmental impact material in a series of composite products and is increasingly used in buildings as an insulating element in exterior wall construction [13-15].

In addition, it should be noted that the thermal decomposition, during the brick manufacturing process, of the pore-forming agents (drying and firing stages), leads to an increase in the porosity of the material [16] and, therefore, to an increase in insulating capacity [17-19].

Current environmental sustainability policies and associated concepts of bioclimatic architecture, as well as social concern for general environmental aspects (global warming, increased damage to the ozone layer and the accumulation of waste), have caused the construction industry to be increasingly sensitive and obliged to consider new construction materials that reduce energy consumption, innovating in the creation of products of a sustainable nature. In fact, in Europe, the construction sector is responsible for 40-45% of primary energy consumption, which contributes to significant emissions of greenhouse gases [20] [21].

In this line of research, similar studies have been carried out that applied the LCA technique to the production of cellulose nanofibers as an organic biofuel additive against the use of plastic materials, observing reductions in greenhouse gases by up to 75% and reducing production costs by 12%, as well as improving the energy efficiency of production between two and five times [22]. In addition, the LCA model is currently being applied in numerous studies like that of Tsinghua University to calculate fossil energy consumption in the life cycle and greenhouse gas emissions in China [23]. Therefore, it is necessary to evaluate the environmental impact of construction materials using the LCA technique. Many scientific studies that use the LCA methodology compare different materials together, highlighting those with less impact on the environment [24, 25].

The objective of this research is to apply the LCA method to new samples of clay with the incorporation of biomass, to determine new construction materials from the point of view of sustainability. [26].

To this end, a comparative study has been carried out between a sample made exclusively with 100% clay (BYRC) and a mixture composed of 15% barley components (leftovers that remain after the seed has been extracted from the cereal) and 85% of the base clay mixture (Brick with red clay (BYRC)) called BB15 (Barley bagasse 15).

These materials have been selected due to their low cost, availability and close location to the research centre. Also, in the firing process, the biological material degrades under the thermal effect, producing pores that increase the sample's insulation capacity [27], enabling the improvement of the thermal bridge and energy efficiency in the construction of sustainable housing. [28],

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2. Materials and Methods

In this study, samples of ceramic material have been used, made with products and resources from the nearby geographical area (Bailén, Jaén). The manufacturing process, including the grinding, sieving, drying and firing of the materials has been carried out in a similar way to industrial manufacturing so that the results can be extrapolated to greater production levels.

LCA is an adequate methodology to determine the environmental impact that occurs throughout the life cycle of products, services or processes. It also allows the determination of the impact of any of the phases independently from the rest.

2.1. Development of fired clay samples

The first sample is a reference sample without additives (BYRC). It contains 100% clay which originated in Bailén (Jaén, Spain). Clay has been provided by a company in the sector. First, it will be crushed to obtain a powder with particles of approximately 3 mm, to promote thermal conductivity [29, 30].

For the second sample (BB15), 85% of the reference sample (BYRC) was separated, to which 15% of barley bagasse was added as an additive and mixed in a laminator to improve the homogeneity, obtaining a sample with a biological basis.

The bagasse, provided by the Heineken brewery (Jaén, Spain), located in Jaén’s capital, was crushed and sieved to obtain a milling of less than 0.5 mm. The amount of incorporated additive was chosen in line with previous studies [31].

The required amount of water was added to obtain the desired moisture and plasticity that are necessary to avoid defects in the structure during the process. Subsequently, the samples were modelled by an extrusion process in the form of tablets (175 x 79 x 17 mm), dried up to 105° C and finally fired by increasing the temperature progressively during 11 hours until the maximum temperature of 920° C, remaining for 1 h afterwards, according to the industrial recommendations of the ceramic sector.

2.2. Life-cycle analysis (LCA)

The life cycle analysis was carried out using the ISO 14040 standards [32] defining the principles and framework, and according to ISO 14044 [33] describing the different stages of the analysis. [34].

2.2.1. Definition of objective and scope

The evaluation of the life cycle was carried out following the process to obtain the clay samples. To analyse and compare the environmental impact of the different formulations and identify the unit of the process that presents the strongest environmental impact, in an ecological design approach, as the main environmental benefit in construction is to reuse the bricks and recycle the aggregates [35].

In order to build the inventory of production and establish the scope of the study, the functional unit is defined as the production of 1kg of clay with a fixed thermal resistance.

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The LCA methodology allows the determination of the environmental impact of the processes, products or systems analysed in different ways. That is, you can analyse certain stages of the life cycle, or analyse the entire cycle. The present investigation will focus only on the impact associated with the production of these new samples, thus performing the analysis known as 'Gate to Gate.'

The system studied uses raw materials from the laboratory (clay, sand, water and vegetable matter) and takes into account the energy consumed in production (sieving, drying and firing), to overcome the potential limitations, the initial hypotheses are defined as follows:

- The electricity used considers that the production mix corresponds to the Spanish energy production system.
- The cleaning of the different devices used in the process is dismissed since it is not a considerable percentage.
- The transport of material from the quarry, or from the factory to the laboratory, is not considered as it is a gate to gate study.

The evaluation of the life cycle impact of the use of bagasse for brick construction was carried out using the LCA SimaPro software 8.30 [36], which is widely used [37].

2.2.2. Life-cycle inventory

For the life cycle inventory, all inputs and outputs of the system were listed for the different stages of the life cycle. Figure 1 shows a flow diagram of the different steps of the process with the associated flows and Figure 2 shows the inputs, also called foreground data that have their own life cycle. These environmental impacts (background data) are taken into account for the overall evaluation of the life cycle of the product.

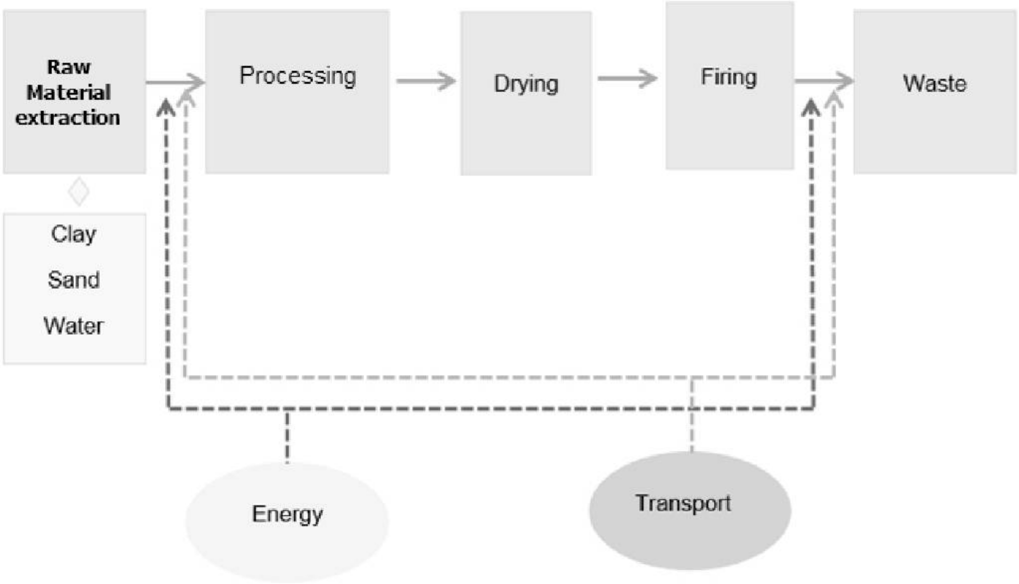

Figure 1. Clay cycle.

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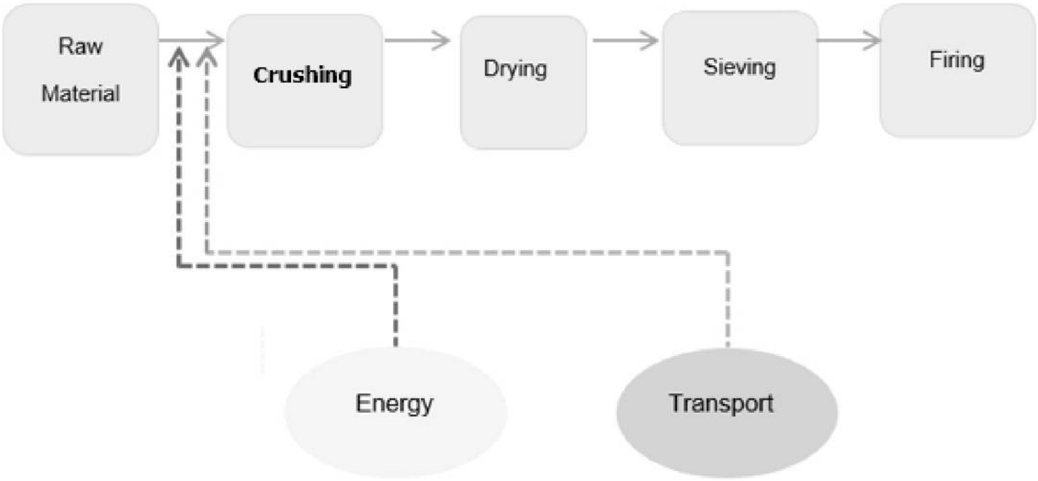

Figure 2. Barley cycle.

The inventory data was obtained directly from the experiments or through the use of data collected from industrial producer partners or from bibliographic references (Table 1). The consumption data of the different processes are shown in Table 2.

Table 1. Inventory data

	BYRC (kg)	BYRC (%)	BB15 (kg)	BB15 (%)
Mix clay + sand	0.143	100 %	0.122	85 %
Barley			0.021	15 %
Water	0.317	100 %	0.317	100 %

Table 2. Total energy consumption data of the different processes

	BYRC (kwh)	BB15 (kwh)
Crushing	0.250	0.333
Drying	0.083	
Firing	25.400	21.850
Total	**25.730**	**22.183**

Due to confidentiality issues, all process data provided by industries cannot be detailed in this publication for either the clay mixture or for the vegetable pore forming agents.

2.2.3 Impact evaluation

With the data previously provided, an evaluation of the environmental impact of the samples is carried out using the software Simapro 8.30. We will carry out a comparative study using two methodologies to check for possible deviation in the results. The ReCiPe Endpoint v 1.12 methodology will be used first. This methodology evaluates the damage caused in four impact categories, whose characteristics are described in Table 3. Impact 2002+ v2.12 will be the second analysis methodology

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Table 3. Indicators of impacts according to ReCiPe Endpoint v1.12

Impact category	Category indicator	Measurement units
Quality of the ecosystem	FDP*	FDP / m2 x year
Human health	DALY**	People / year
Natural resources	Damage to resources	MJ/Kg
Abiotic resources ***	Exhaustion	Kg

* Fraction of potential disappearance of the ecosystem per m2 and year.

** Disability-adjusted life year: Reduction of years of life per person / year

*** Climatic, geological and geographical resources. Biodiversity.

3. Results and discussion

The objective is to compare the environmental impact of the two formulations developed. The functional unit has been defined as well as the production of 1kg of the porous sample, corresponding to that of the reference sample, without the vegetable agent.

3.1. Methodology ReCiPe Endpoint v1.12

Once the inventory data has been entered, the Simapro software and, using the first methodology, the ReCiPe Endpoint v1.12, provides the results shown in Table 4, where the contribution amounts provided by the different clay samples can be analysed in each impact category. This data has been provided by the program, once the different amounts of raw materials and processes have been introduced.

Table 4. Analysis of the energy and non-energy resources of the comparative cycle of clay samples as a base.

Non-energy resources	BYRC	BB15	Energetic resources	BYRC	BB15
Ammonium (g)	0	3.10	Low radioactive waste (mg)	399.75	344.64
NH4 (Kg)	0	0.026	Water power (g)	317	317
Calcite (g)	0	1.94	Barley (Kg)	0	0.15
Crushed stone (g)	14.43	10.54	Electric mix(MJ)	92.62	79.85
Ni (Kg)	16.15	13.92	Urea (g)	1.60	1.82

The general comparison of the scenarios represents the relative percentage in each impact category. The most impressive scenario in the category represents 100% and the others are calculated according to the latter. The comparison with the scenario of the BB15 sample, using the ReCiPe Endpoint v1.12 method is presented in Figure 3, for the characterisation of the impact and in Figure 4 for the characterisation of the damage.

The reference sample, without a pore-forming agent, shows the maximum impact in the 12 impact categories. Therefore, in the three categories of damage, human health, ecosystem and resources, with a gap or difference from the other scenarios between 10% and 22%. In Figure 3, the impacts of the two samples are compared showing that, in general, the base sample (BYRC) produces a greater impact than the sample to which biological material has been added (BB15). Likewise, the electricity consumption is higher in the base sample, so the aspects relating to resources are affected in the final result.

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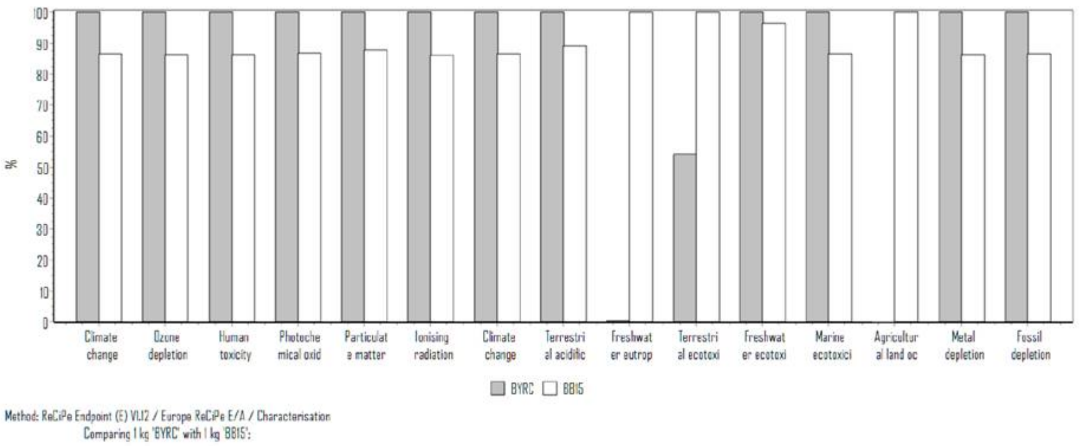

Figure 3. Comparative impact of the samples analysed with the methodology ReCiPe Endpoint v 1.12.

In Figure 4, the impact of the samples to human health, ecosystem and resources can be observed. In the base sample (BYRC) the impact is greatest, with human health and resources, showing the greatest difference. This is motivated by the need for fewer raw materials in the development of the samples. The third indicator of this ReCiPe Endpoint v 1.12 methodology shows that the impact on the ecosystem is similar in the two samples.

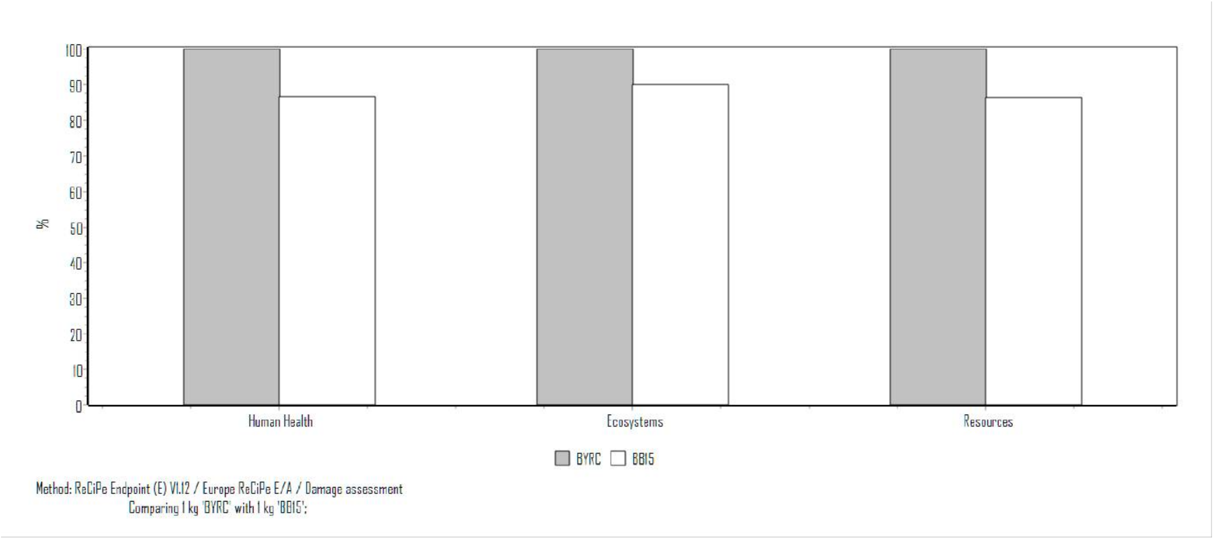

Figure 4. Damage assessment of the samples with the methodology ReCiPe Endpoint v 1.12.

Performing an analysis of the samples using the single score, it is easy to determine the impact percentages that each sample has on the three aspects to be considered with the ReCiPe Endpoint v 1.12 methodology. As can be seen in Figure 5, the base sample (BYRC) has the greatest impact.

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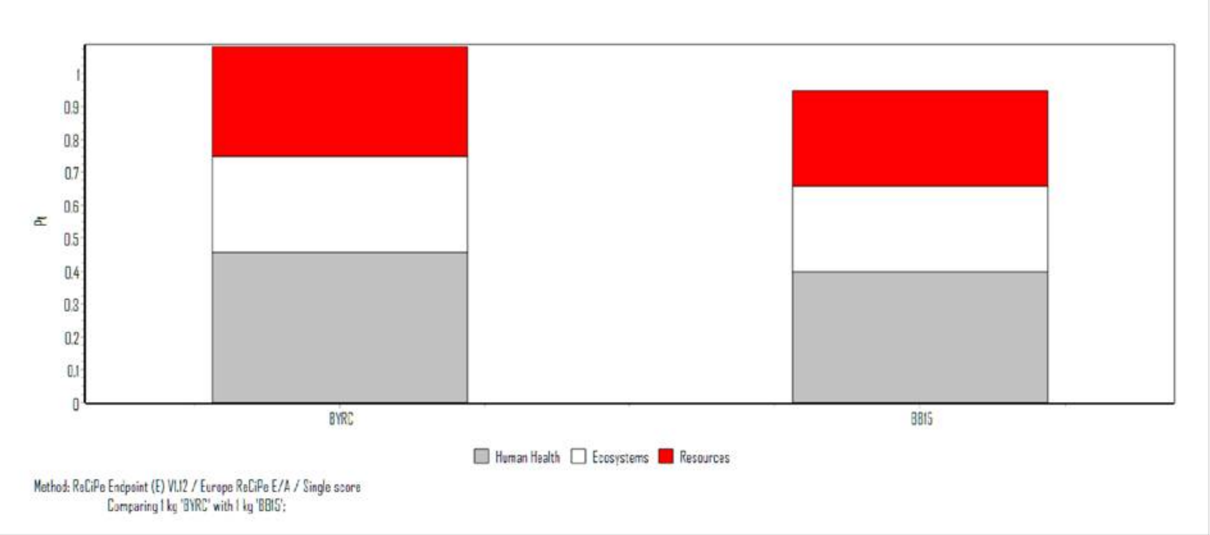

Figure 5. Single score with the methodology ReCiPe Endpoint v 1.12.

Results in figures 6 to 8 show the quantities of the flows that produce the greatest impact; resources, air emissions and impact on human health. The greatest impact is the emission of CO2 into the atmosphere, mainly due to the electrical energy consumed in the firing phase, followed by the emissions of Methane, Sulfur Dioxide and Nitrogen Dioxide.

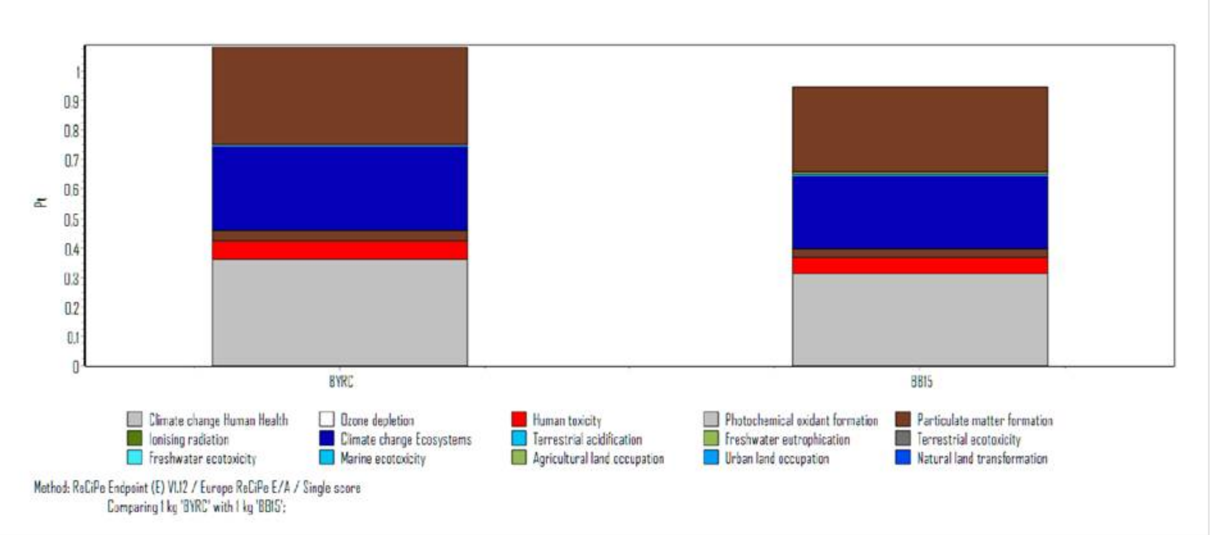

Figure 6. Weighting and quantity of resources with the methodology ReCiPe Endpoint v 1.12.

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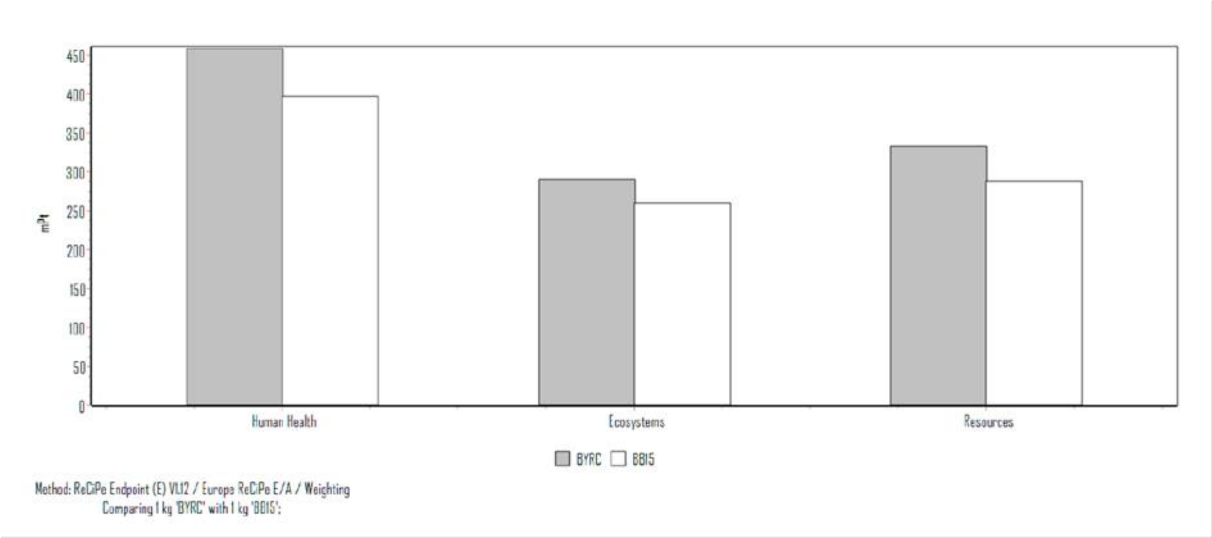

Figure 7. Weighting of emissions to the air with the methodology ReCiPe Endpoint v 1.12.

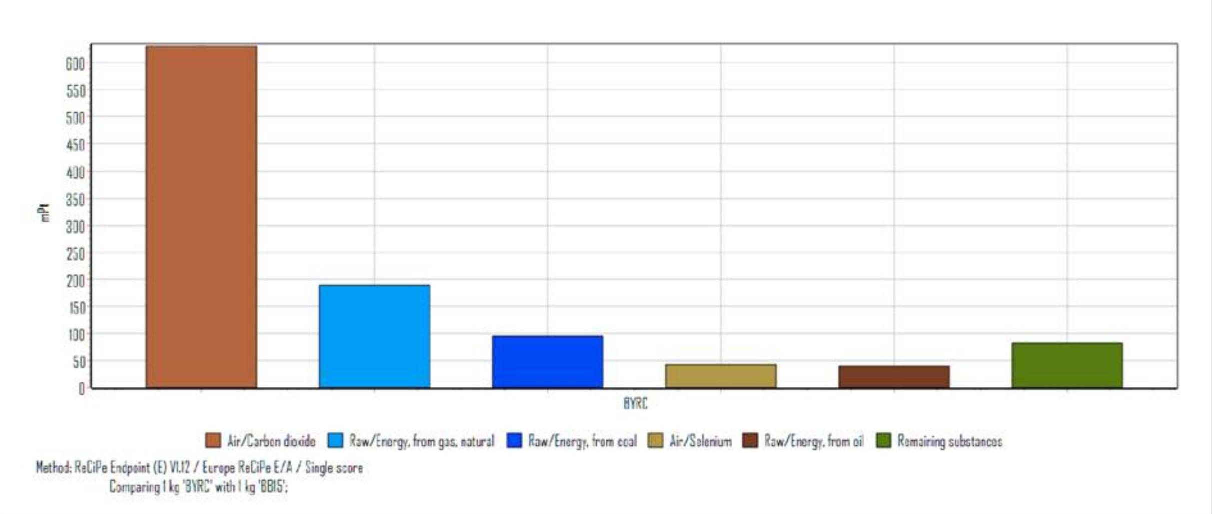

Figure 8. Impacts on the ecosystem with the methodology ReCiPe Endpoint v 1.12.

3.2. Methodology Impact 2002+ v2.12

The Impact 2002+ methodology provides us with additional information about factors that influence climate change. The results obtained are analysed below.

Figure 9 shows that of the 15 indicators, 11 contribute the greatest impact and correspond to the base sample (BYRC), the samples with biological material show a higher impact in only 4.

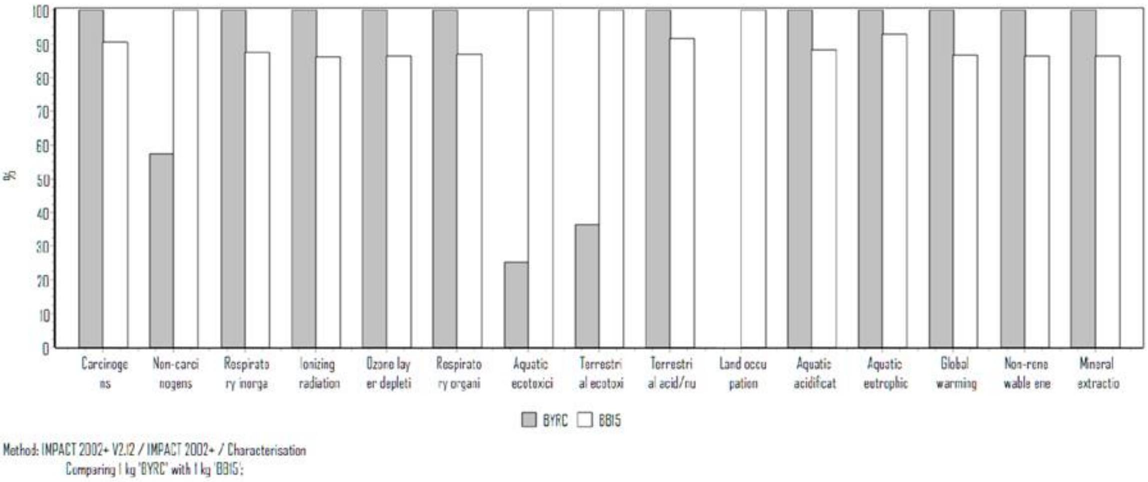

Figure 9. Comparative impact of the samples analysed with the methodology Impact 2002+ v2.12.

We can see in Figure 10, how the results are practically similar, with the addition of the information provided by the methodology on climate change.

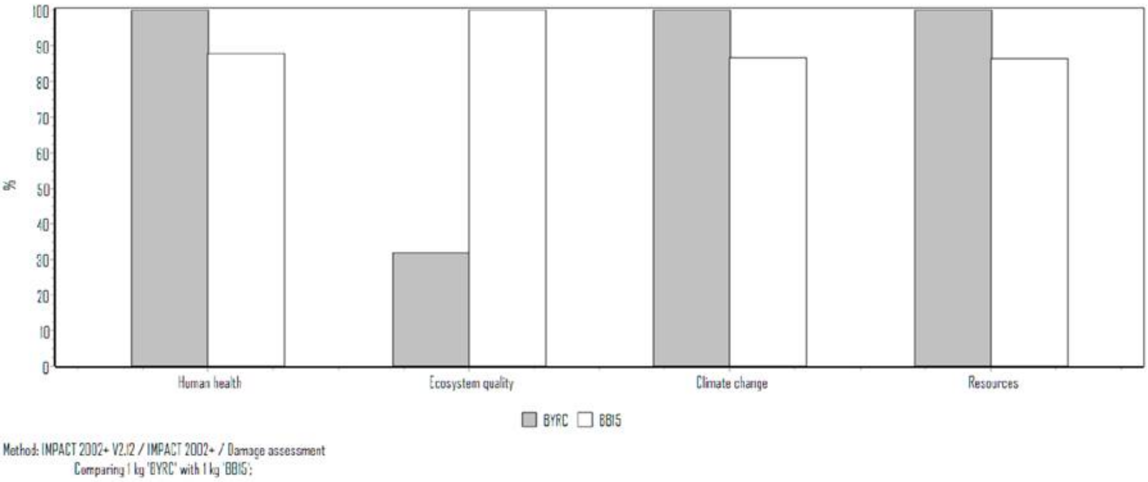

Figure 10. Evaluation of the damage of the samples with the methodology Impact 2002+ v2.12.

Figure 11 shows how the greatest impact occurs on resources, both for the extraction of raw materials and for obtaining the raw materials necessary to produce the electrical energy needed in the manufacturing processes of the new material.

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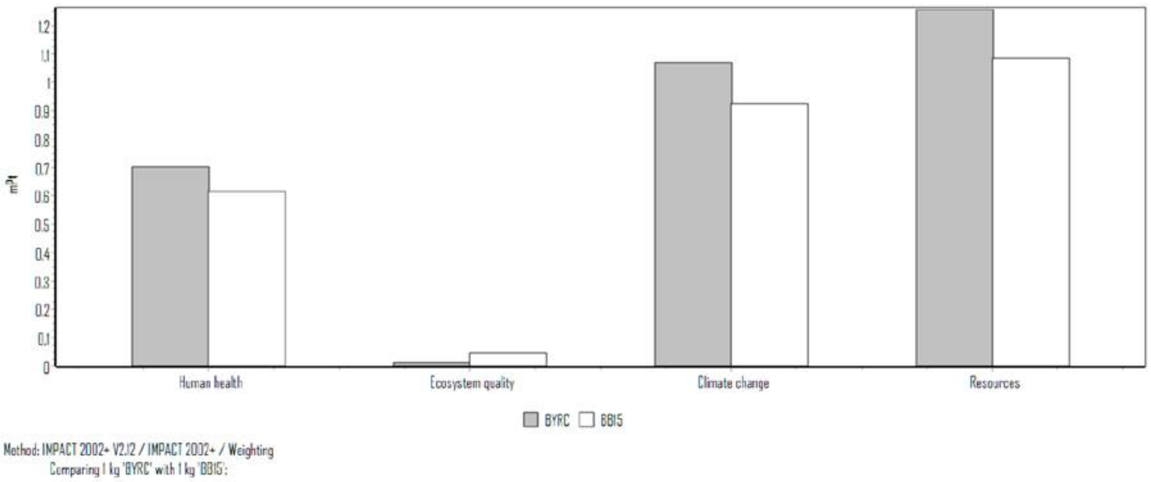

Figure 11. Weighting and quantity of resources with the methodology Impact 2002+ v2.12

As a summary, in Figure 12, we note that a considerable improvement is achieved in the reduction of impacts in all categories, the most considerable being that of resources.

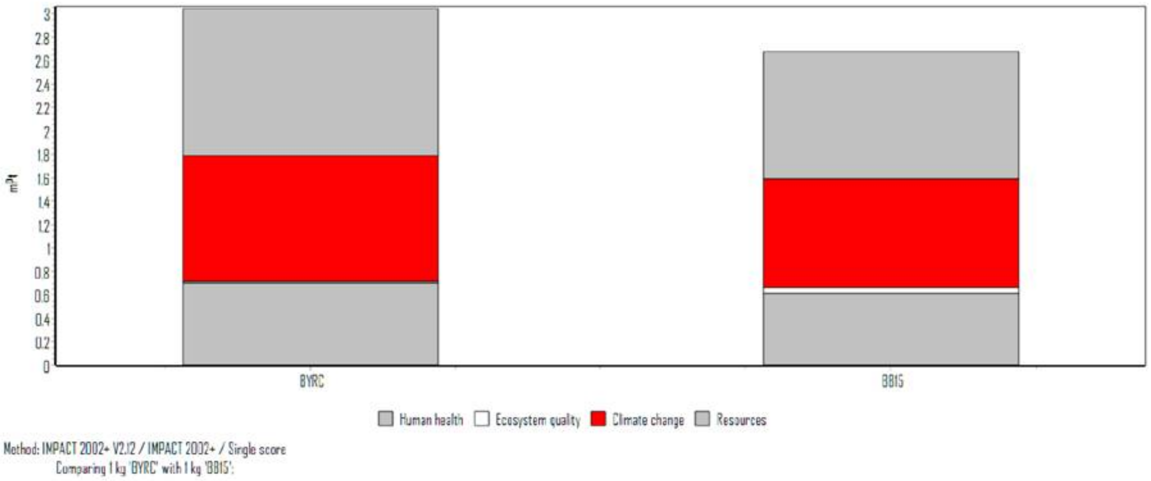

Figure 12. Single score with the methodology Impact 2002+ v2.12.

5. Conclusions

In this investigation, the environmental impacts of two brick samples have been studied using life cycle analysis, one with a traditional make-up and the other with a mixture of clay and a biological agent. In addition, the results have been verified using two different methodologies.

For the biological sample, a vegetable additive, specifically barley bagasse, has been incorporated into a traditional clay base, to check for improvement in the aspects of insulation, weight and environmental contamination. The study focuses on the environmental impact of the two formulations through a Life Cycle Analysis, using the ReCiPe Endpoint v 1.12 characterization method and the Impact 2002+ methodology. It is observed that the incorporation of plant additives into the matrix, decreases the impact by 15% to 20% compared with the reference sample.

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Therefore, a clear improvement of the environmental impact is possible using a biological vegetable and clay mixed brick. It shows a reduction in the impact generated by obtaining and transforming the raw materials. In addition, this would be a very interesting innovation in the field of new materials used in bioclimatic architecture. Even so, other aspects such as mechanical resistance, bending resistance and thermal conductivity should be considered in future studies.

Thus, according to the results obtained and taking into account both general sustainable development and regulations on energy efficiency [38, 39], it is deduced that it is necessary to develop new materials using by-products or waste that facilitate their incorporation into the cycle of industrial life, since it would constitute a reduction of emissions and a reduction in energy and resource consumption.

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