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Life cycle assessment of regional brick manufacture

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ABSTRACT: This document presents a Life Cycle Assessment (LCA) study to quantify the environmental cradle-to-gate impact of the manufacture of brick for the construction industry, produced with material of igneous source. Its mineral composition and thermal isolation properties were characterized for use in real estate construction. The LCA results for brick manufacture using this material identified the greatest environmental impact to be associated with material extraction and its proportional cement content. Additionally, this document presents an evaluation of the environmental impact of the manufacturing process by comparing traditional fired clay brick and brick of the material under study. In conclusion, the studied material shows thermal insulation qualities and suitability for the manufacture of bricks with low incorporated energy.

KEYWORDS: Life Cycle Assessment; Brick; Environmental impact; Thermal properties

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RESUMEN: *ACV de la manufactura regional de ladrillos*. Este trabajo presenta un estudio de Análisis de Ciclo de Vida (ACV) para cuantificar los impactos ambientales de la cuna a la puerta de la manufactura de ladrillos para la industria de la construcción, fabricados de un material de origen ígneo. Se caracterizó su composición mineralógica y propiedades de aislamiento térmico para ser usado en la construcción de inmuebles. Los resultados ACV de la fabricación de ladrillos de este material, identificaron la mayor contribución a los impactos ambientales asociados a la extracción del material y la cantidad proporcional de cemento. Adicionalmente, se presenta una evaluación comparativa del impacto ambiental entre la manufactura de un ladrillo tradicional de arcilla cocido y de un ladrillo del material en estudio. En conclusión el material estudiado muestra cualidades de aislamiento térmico y es adecuado para la fabricación de ladrillos con baja energía incorporada.

PALABRAS CLAVE: Análisis de Ciclo de Vida; Ladrillo; Impacto ambiental; Propiedades térmicas

1. INTRODUCTION

In response to evident climatic change, reduction and efficient use of energy is essential. The construction sector is one of the least sustainable, as construction materials generate high environmental costs due to the consumption of natural resources and energy, as well as waste generation (1). For this reason, increasing the energy efficiency of buildings is key to reducing their environmental impact (2). Mercader et al. (3) estimated the energy consumption per constructed square meter, for the manufacture of the materials used in the most common types of buildings in Seville, and noted that the results in similar lifecycle studies depend mostly on the geographic area.

According to Klemeš et al. (4) to carry out improvements aimed at leading the lifestyle of a sustainable society, clean production must be based on the global vision provided by Life Cycle Assessment (LCA). Huedo et al. (5) analyzed and classified LCA tools that support planners when selecting sustainable building solutions. Other authors have used this tool to evaluate the environmental impact of different phases in the manufacture of the most commonly used building materials (6–12). Rivela et al. (2) analyzed and quantified the impact of green roofs on improving the energy efficiency of buildings. Buenviste et al. (13) carried out a study on the environmental impact of the manufacture of glazed floor and wall tiles, from the extraction of raw material to the demolition phase, finding that the manufacturing phase has the greatest impact on the life cycle.

Several laboratory studies have been carried out on waste and recycled materials, in the aim of applying them to construction, thus reducing the environmental impact, as well as taking advantage of their energy properties during their manufacture (1, 14, 15).

Efforts to improve the performance of buildings and reduce their environmental impact have been focused on increasing energy efficiency (2). Thermal insulation plays a key role in improving the energy efficiency of buildings (16). Stéphan et al. (17) analyzed the thermal inertia of old limestone buildings before and after insulation with hemp-concrete, a natural cellulose fiber compound. Marrero et al. (1) states that from the perspective of environmental impact, the construction sector and users, must make a common effort by choosing materials of low energy consumption based on their life cycle.

Although several life cycle studies of broadly used building materials have been carried out in Mexico (18–20), the information available on its environmental impact is scarce. Particularly, the 2010 census reports a housing stock of 1,228,567 houses in the state of Chihuahua, Mexico which registered a 20% increase in 10 years (21), implying an energy demand both during construction and operation.

Due to the urban expansion of the city, subject to the demand in housing and services, new building material options with thermal insulation properties, available in the region, are required. The LCA method has been used in this study to quantify the environmental impact associated with the manufacturing process for a brick of igneous material. Proof of the thermal insulating properties for construction was obtained by the characterization of its mineralogical composition and by corroborating this experimentally.

2. MATERIAL AND METHODS

The mineralogical composition and the thermal insulation properties of an Altered Rhyolitic Tuff (TRA for its abbreviation in Spanish) sample extracted from a mineral deposit of the region (28° 48′ 36″ N, 105° 54′ 3.0″ W) was characterized. A PAN analytical (X'Pert PRO MPDX'Celerator) X-ray spectrometer was used to identify the components present. The density was measured by means of liquid displacement using an Ohaus analytical balance (Explorer). Dispersive energy detector analysis (EDS) was used on an SEM (JEOL JSM-7401F) microscope to identify the elements contained therein. The thermogravimetric and differential scanning calorimetry (TGA-DSC) analyses were performed on a TA instruments (SDTQ600). The thermal conductivity was measured using Unitherm (2022) equipment. The test was carried out according to standard ASTM -E -1530 (7 cm in diameter and 3 cm wide cylinder). The diffuse reflectance tests (wavelengths between 230 nm and 1100 nm) were performed using Perkin Elmer (Lambda 10) equipment with an integrating sphere (Labsphere).

Two block type walls were built, with structural units of conventional residential size (19.5 cm, 19.5 cm, 40 cm). One was made from traditional calcite blocks (a hollow construction block made with concrete) and the other with TRA blocks, in the aim of making an *in situ* comparison of the thermal insulation of the construction. This experiment was performed in summer in such a way that the wall surface was frontally exposed to the sun. The differential temperature was measured on the exposed wall surface and at a depth of 2.54 cm ($\Delta T = T_{int} - T_{ext}$).

2.1. Life Cycle Assessment (LCA) Methodology

The LCA includes the determination of potential impacts by compiling inputs and outputs of a product or system throughout its lifecycle. The studies comprise four phases: objective and definition of scope, inventory analysis, impact evaluation, and interpretation of results. This study presents the analysis of the environmental impact of TRA brick manufacture according to international standards (22–24).

The objective of this LCA study was to evaluate the environmental impact of LCA brick manufacture. The scope of the "from cradle-to-gate" approximation is from the extraction process to the finished product shown in Figure 1. The functional unit is the basis for comparing the different systems in an LCA study; its main purpose is to provide a reference that relates the inputs and outputs of the system (22). The functional unit was specified as the production of a brick manufactured with natural igneous rock, of standard size (7 cm, 14 cm, 28 cm) composed of: 3 kg of TRA, 0.01 kg of Portland cement, and 333 ml of

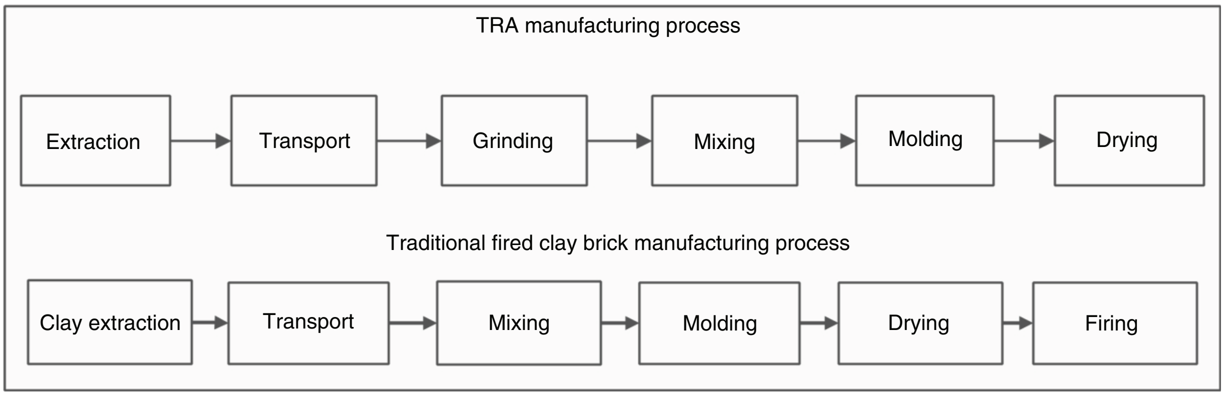

FIGURE 1. Diagram Process of TRA brick and fired clay brick manufacture.

water under normal operating conditions in Aldama City, Chihuahua, Mexico.

A Life Cycle Inventory (LCI) was created based on information from the manufacturing process for the production of igneous material brick. The LCI data for extraction, material transportation and emissions from cement production were calculated using emission factors AP42 (25). The energy consumption of the engines for this manufacturing process was provided by the local TRA brick producer. Emissions associated with electricity production were calculated with emission factors (25) and information from the combined cycle plant "El Encino", which provides the electricity for the area of study.

The LCA was performed using SimaPro 7.3 software and parameters from the Eco-invent v2.2 database. The potential environmental impacts were estimated according to the impact evaluation methodology Ecoindicator 99, which models the damage from the cause-effect chain, evaluating three areas of damage or impact: Human Health, Ecosystem Quality, and Resources, making it suitable for the analysis of the obtained results. The method was developed by PRéConsultants as a damage oriented approximation: Egalitarian, Hierarchical, and Individualistic. Egalitarian and Individualistic approaches are closer to reality than the Hierarchical approach (26). The Egalitarian approach to Eco-indicator 99 was used in this study. Although the use of LCA tools could offer a restriction in regions different to those of its origin, due to the fact that the environmental impact of the materials may vary depending on the territory and location of the raw materials (5). Exceptions are damages to resources, damage due to climatic changes, ozone layer depletion, air emissions of cancerous persistent substances, and inorganic contaminants which have a great air dispersion range (27). Lopsik (28) concluded in his research that the limits and alleged facts during the LCA study should be taken into account for the interpretation of the results of the impact evaluation.

3. RESULTS AND DISCUSSION

3.1. Mineralogical characterization and thermal insulation properties in construction

The quantitative and semi-quantitative analysis by X-ray diffraction (DRX) determined the abundant presence of tosudite, clinoptilolite (zeolite), calcite and quartz besides other minor phases such as cristobalite, sanidine and sodium anorthite (Figure 2). The density of material was determined as 1.835 g/cm^3. The EDS chemical analysis confirmed the presence of some of these elements (Figure 3).

From the study performed on the TRA material sample by TGA/DSC (Figure 4) the retention of water molecules is suspected, especially by the presence of –OH groups in the tosudite (29).

Water retention is proved by the analysis of the percentage weight loss, a phenomenon of absorption/desorption which causes a dimensional change. The TGA and DSC curves show the greatest change in weight at a temperature of less than 200 °C and endothermic peaks at 80 °C and 160 °C attributed to water evaporation, where the first and second peaks represent the maximum evaporation rate of absorbed and related water thus demonstrating the hygroscopic nature of the material. The weight loss between 200 °C to 600 °C could be attributed to the process of dehydroxylation, as endothermal decomposition of calcite occurs between 600 °C and 800 °C.

The fundamental parameter for thermally isolating materials is the thermal conductivity k. A lower numerical value enables the application of relatively thin coatings with high thermal resistance [r=1/k] (16). The thermal conductivity analysis of the TRA brick was 365 mW/m·K. According to national and international standards the typical thermal conductivity values for fired clay bricks range from 360.5 mW/m·K to 1471 mW/m·K, and from 1153 mW/m·K to 6201 mW/ m·K in the case of concrete (30–32).

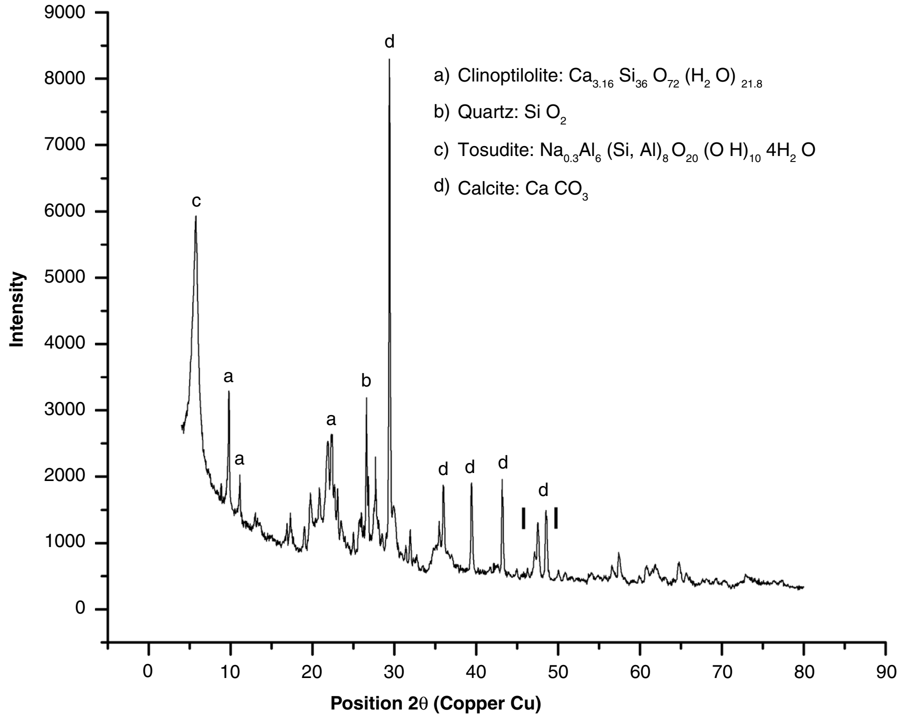

FIGURE 2. XRD pattern of TRA sample.

The results of the reflectance tests are illustrated on Figure 5, showing that the TRA material reflects between 20% to 35% of the radiation contained between the wave lengths from 230 nm to 300 nm in the average Ultraviolet frequency (UV-B). From 300 nm to 380 nm in the near Ultraviolet frequency (UV-A) a 45% increase in reflectance is observed. From the visible spectrum and up to 110 nm the near infrared, a reflectance percentage between 80% and 90% can be seen, whereas the other materials reflect less than 75% within the same range.

In the experiment to compare the thermal gradient of the two types of wall (Figure 6), observations showed that the wall built with TRA material registered a differential temperature of 5 °C, whereas that built with commercial brick was 2.5 °C, thus proving the thermal insulating ability of the TRA material, which could be exploited during the usage phase of buildings.

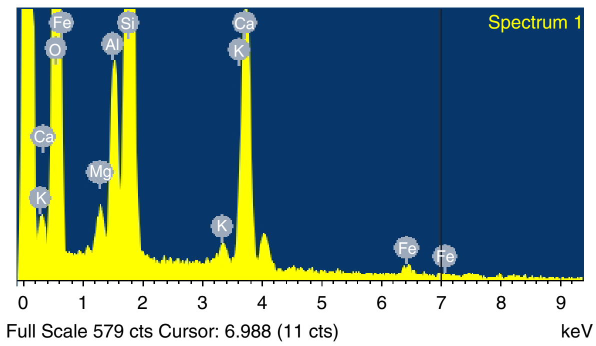

FIGURE 3. EDS spectrum of TRA sample.

3.2. Life Cycle Impact Assessment (LCIA)

Figure 1 shows the steps in the manufacturing process of a TRA brick. The necessary information for raw materials, dosage and types of material, as well as the energy input was obtained with the help of the manufacturer. The LCI manufacturing process shown on Figure 7 was created based on this information. It is important to know the environmental impact of the electricity generation, which must be calculated for each research case, and which depends on the local generation technology and the distribution network available in the area.

The LCIA stage includes the assignment of the results of the LCI to the impact categories selected, and the calculation of the potential environmental impact for each category. The results presented on Figure 8 show that the greatest contribution in all impact categories corresponds to material extraction, which ranges from a contribution of 27% to 98% in the categories shown (except in the fossil fuels category). This is due to the use of heavy machinery and transportation to the manufacturing site at a distance of 5 km. Portland cement which forms part of a TRA brick represents considerable impact due to the fuel consumption reflected in the fossil fuel category (99%), as well as being present from 4% up

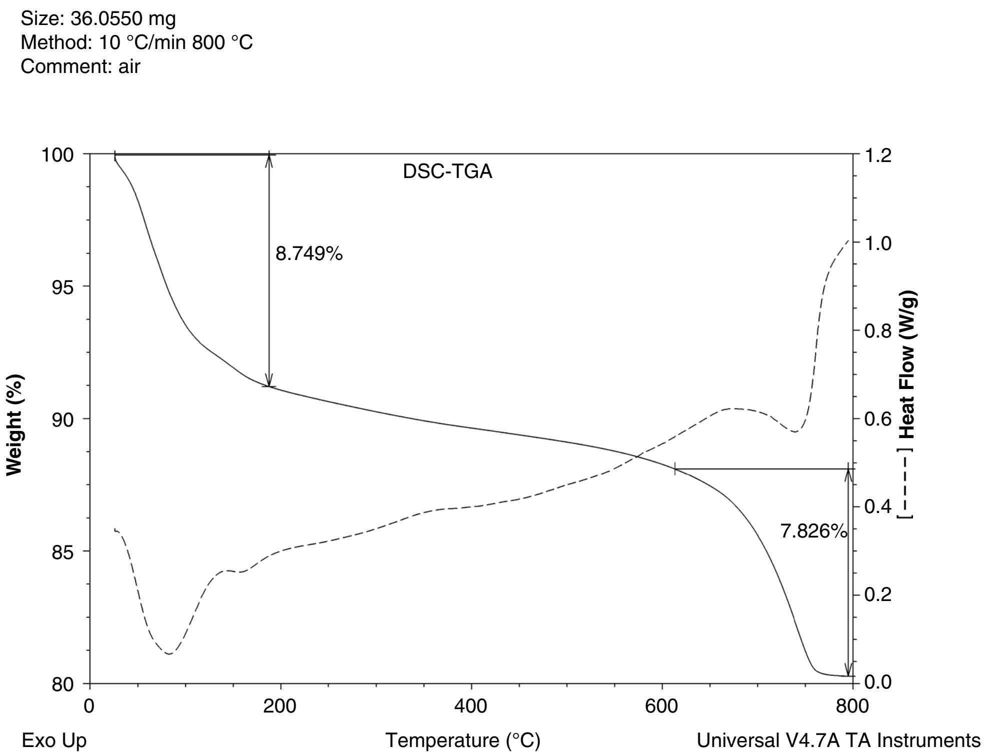

FIGURE 4. TGA/DSC curves of TRA material.

to 55%, except in the categories of land use, minerals and radiation. The reason for these impacts is related to high emission levels and the cost of energy in the cement production process (2).

Electricity is found in all categories with contributions ranging from 2% to 40%. Transportation to the brick manufacturing site and the water supply have a less considerable impact with contributions no greater than 9%.

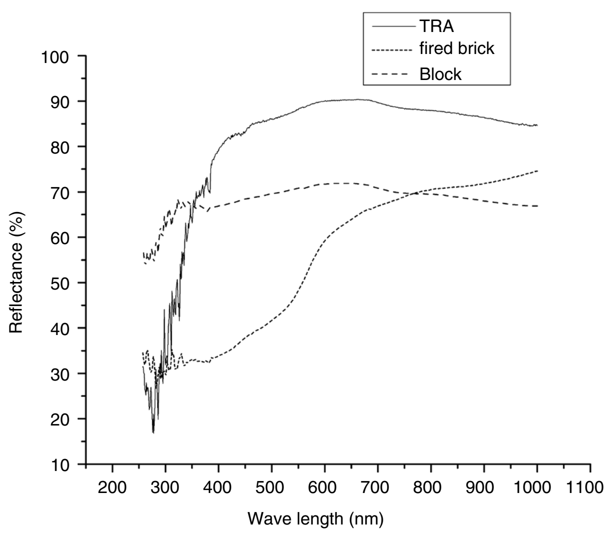

FIGURE 5. Reflectance tests of TRA material.

The manufacturing process for a fired clay brick (Figure 1) was compared with the manufacture of a TRA brick using LCA methodology. The main difference betewen these two manufacturing processes is the firing stage, which is only present in the manufacture of the clay brick and is performed in intermitent traditional kilns, which contribute greatly to pollution and environmental deterioration. Fired bricks are widely used for building in Latin America, India, and China (33) for its lower thermal conductivity in comparisson with cement based bricks. Table 1 compares the environmental impact of the damage categories of TRA brick and fired clay brick manufacture. These calculations were made using the Ecoindicator 99 method, the Eco-invent v2.2 database and the emission factors (25). The emissions of a brick kiln (CO, CO_2 and O_2) were determined *in situ* with a gas analyzer and elemental analysis of fuel (C, H, N, and S) was

TABLE 1. Life cycle damage assessment comparison between fired clay and TRA brick manufacture

	Manufacturing process	
Damage category (units)	**Fired clay brick**	**TRA brick**
Human Health (DALY)	25.02	1.39E-07
Ecosystem Quality (PDF*m^{2}yr)	18.45 E+03	7.43E-03
Energy sources (MJ surplus)	9.41E-02	3.17E-03

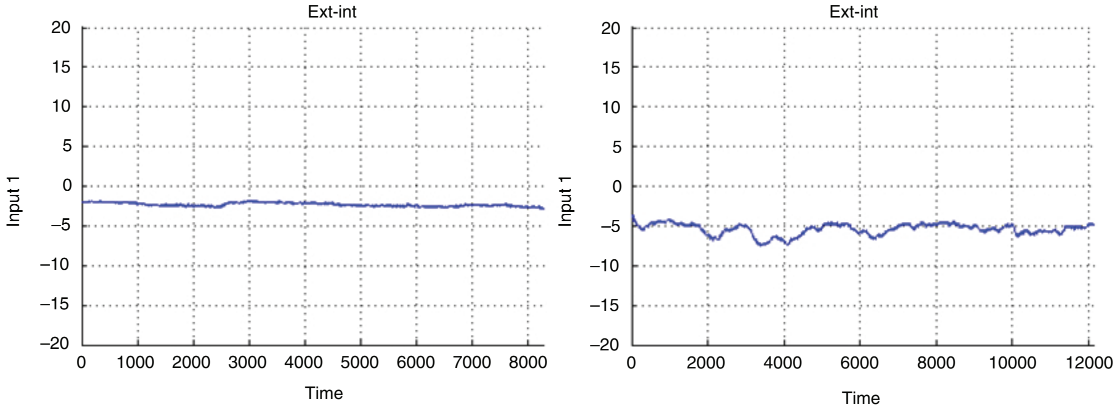

FIGURE 6. Differential heating Test, (a) residential block wall, (b) TRA block wall.

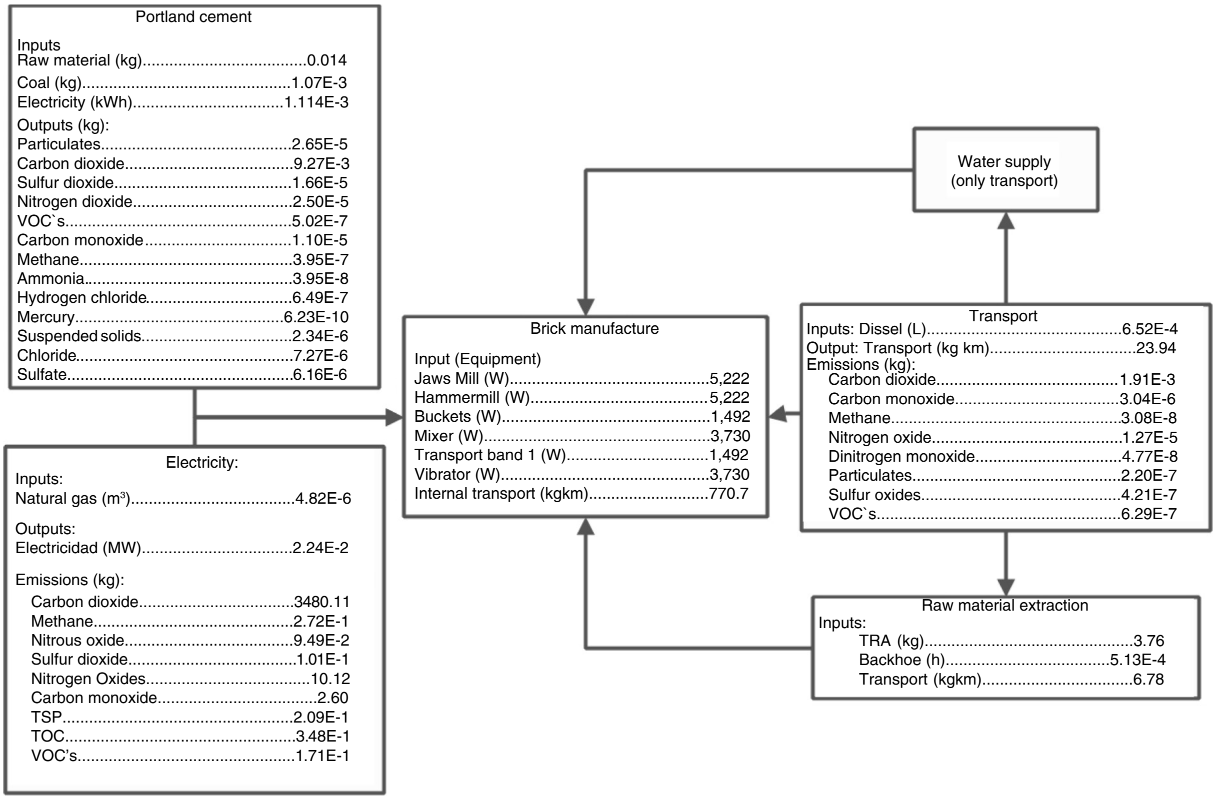

FIGURE 7. Life Cycle Inventory process.

carried out using a gas chromatography. With the help of some local producers, the information calculated, and collected experimentally, contributed to the development of the clay brick's LCI (not included in this article).

The category of damage to Human Health, which includes the number and duration of diseases, and number of years of life lost due to premature deaths due to environmental causes, is estimated as the number of years of life lost, and expressed in DALY units (Dissability Adjusted Life Years), the index used by the World Bank and by the World Health Organization. The Ecosystem Quality damage category is expressed as the "Potentially Disappeared Fraction of plant species per square meter and year", and calculated in PDF units (PDF*m^2yr), which includes the effect on species diversity and especially for vascular plants and minor organisms. The damage to the resources is expressed as the surplus energy necessary for the future extraction of minerals and fossil fuels in "Mega Joules surplus" units (34).

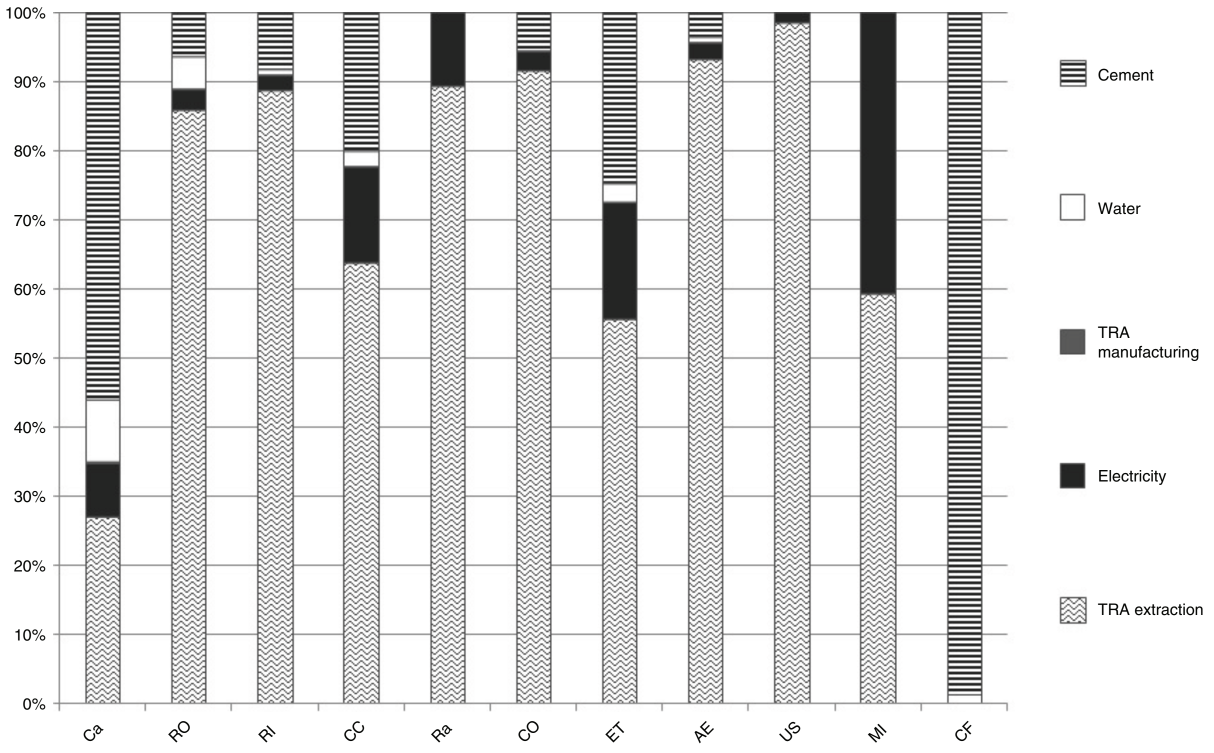

Figure 8. Life cycle impact assessment of TRA brick. CA: Carcinogens; RO: Respiratory organics; RI: Respiratory inorganics; CC: Climate change; Ra: Radiation; OL: Ozone layer; ET: Ecotoxicity; AE: Acidification/Eutrophication; LU: Land use; Mi: Minerals; CF: Fossil fuels.

The impacts quantified as Carcinogenic, Respiratory organic and inorganic, Climatic Change, Ozone Layer Depletion, and Ionizing Radiation (nuclear) contributes to damage to Human Health. The impact of Ecotoxicity, Acidification/Eutrophication, and land use are contained in the Ecosystem Quality category. The impact on mineral and fossil fuel consumption belong to the Energy Source damage category (24, 34–36). The obtained results identified the greatest environmental impact caused by the manufacture of TRA brick, inside the category of Ecosystem Quality damage. Furthermore, in the comparative study a great difference in the Human Health damage category was found due to the high emissions from the firing kiln. No evidence was found of other studies published on the environmental impact of these traditional manufacturing processes, although many of these kilns are still in operation.

4. CONCLUSIONS

- The chemical and mineral composition of TRA material was confirmed by several different techniques. The tosudite contains –OH groups which give the material hygroscopic characteristics which may cause the bricks to crack during their fast drying process.
- The presence of clinoptilolite which can be used as an adsorbent of certain toxic gasses and to improve the physicochemical properties of soils, due to its characteristics and properties, makes the TRA material a good candidate for use in fluid filtration systems, as well as for agricultural use.
- The thermal conductivity of the TRA sample displays better thermal insulation properties than traditional materials and also reflects the radiation of higher energy in an infrared spectrum, as well as in the visible spectrum.
- Potential energy saving appears in the building of TRA walls during the regular operation of buildings, which was proven by the temperature difference of the comparative test.
- According to the LCA the greatest contribution belongs to material extraction. Furthermore, the cement fraction included in the TRA brick represents a considerable impact on the consumption of fossil fuel, as the cement industry demands great energy consumption.
- Although the impact associated with transportation was not significant, the obtained results make it possible to identify the importance of its environmental impact, hence the importance of promoting the use of local material available which minimizes transportation costs,

especially for the large volumes handled in the construction sector.
- From the perspective of comparing LCAs, which involves local aspects of processes, the manufacture of TRA brick shows a lower potential environmental impact than fired clay brick. The results show that the tool is suitable for the evaluation of new construction material by quantifying the impacts of its manufacture.
- The thermal insulation properties and environmental impacts analyzed, identified the TRA brick as a construction material of low incorporated energy which can contribute to the proportional reduction of CO_2 emissions, thus outdoing other traditional materials.
- The use of the LCA methodology, its importance and value, lies in the identification of the impact causes, which are closely linked to the information on processes and supplies, in order to identify where the actions should be focused depending on the impact and its magnitude.
- Future studies are recommended to analyze the environmental impacts considering the use and demolition phases by means of the different LCIA methods, in order to broaden the scope of the LCA study. Particularly the treatment of Construction and Demolition (C&D) waste which has not been an area of interest in Mexico.

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