Environmental Benefits of Using Sewage Sludge in the Production of Ceramic Bricks

Nara Cangussu[1,2,a], Luana Vasconcelos[2,b], Lino Maia[1,3,c]

[1] CONSTRUCT-LABEST, Faculty of Engineering (FEUP), University of Porto, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal.
[2] Center of Exact and Technological Sciences, Civil Engineering Course, State University of Montes Claros (UNIMONTES), 39401-089 Montes Claros, MG, Brazil.
[3] Faculty of Exact Sciences and Engineering, University of Madeira, Campus da Penteada, 9020-105 Funchal, Portugal.
[a] naracan@gmail.com; ORCID: 0000-0002-3442-6224
[b] luannavasconcelos@yahoo.com.br
[c] linomaia@fe.up.pt; ORCID: 0000-0002-6371-0179; corresponding author

Abstract

The production of sludge from the sewage treatment plants is increasing as a result of population increase and public policies to improve the sanitation sector. This sludge presents a potential risk to health and the environment representing major challenge for sanitation companies regarding treatment and final disposal of this material. The solution is in the circular-economy concept: this sludge presents favorable characteristics to be used as raw-material in the ceramic industry. This study seeks to quantify the environmental impacts related to the atmospheric emissions caused and to the consumption of resources when 10% of clay is replaced by sewage sludge in the production of bricks. Life cycle assessment tools were used to establish a comparison between the common scenario of the brick production using ceramic mass only from clay and the scenario with the incorporation of 10% of sewage sludge. The results revealed that the incorporation of the sewage sludge has multiple benefits, regarding the decrease of the environmental impacts in all the categories studied: 15% in the energy savings, 15% in the terrestrial acidification and the formation of fine particles, 10% in scarcity of mineral resources and 8-10% in formation of photochemical ozone.

Keywords: Bricks; By-product; Circular Economy; Environmental Impacts; LCA; Sewage Sludge.

1. Introduction

On a daily basis, domestic and industrial sewage collection and treatment systems generate large amounts of waste, sludge being the main one. One of the biggest challenges of the generated sludge is its proper disposal. Usually, at the end of the process the sludge produced is incinerated, landfilled, or used in agriculture. However, there are projects of sewage treatment plants that neglect the proper disposal of this material , which causes major financial and environmental problems (Duarte 2008). Recycling this waste material and turning it into bricks could reduce the problems of waste disposal while favoring its use in the construction industry (Joo-Hwa 1987; Okuno and Takahashi 1997; Weng et al. 2003; Keerthana et al. 2019). Researches has been carried out to find an environmental friendly material and method, as well as alternative low cost material for building purposes (Joo-

Hwa 1987; Jianu et al. 2018; Areias et al. 2020; Erdogmus et al. 2021; Gencel et al. 2021; Limami et al. 2021; Minh Trang et al. 2021; Zat et al. 2021). An important part of global industrial production results in the production of massive quantities of industrial by-products or other solid wastes and the best way to handle the solid waste is through recycling and reusing it into new products (Kioupis et al. 2018). In addition, these investigations have also shown a significant lower impact towards the environment by incorporating these wastes into fired clay brick (Azevedo et al. 2020; Mendes et al. 2019; Kadir and Rahim 2014).

The sludge is the result of processes of primary settling or secondary in the sewage treatment systems, not including any solid waste generated in the procedures of de-sanding, railings and screening (CNMA 2021). Thus, its composition can vary according to the treatment used in the plants and the origin of the sewage (França Junior 2008). Furthermore, the sludge may contain heavy metals, microorganisms, pathogenic and toxic organic compounds which present major limitations on the correct choice of final destination for this waste (Araujo 2008).

According to Resolution 375 of the National Council of Natural Environment of Brazil (CONAMA), the sewage sludge presents great risks to health, through the environment and can lead to the proliferation of harmful vectors (CNMA 2006). Because of this, the disposal of this material demands appropriate technologies, studies on the environmental impacts that may be caused, as well as cost analysis of the processes to be employed.

The allocation of the sludge to landfill lacks many specific cares, such as the choice of the site, the project to mitigate the percolation of the material leachate, determinations for the treatment of gases and the leachate generated, among others (Araujo 2008). According to Mateo-Sagasta et al. cities produce large amounts and the quality of the wastewater depends on their source, the way in which they are collected and the treatment they receive. The final fate of these wastes is also very diverse. The resources embedded in the approximately 330 km^3/year of municipal wastewater that are globally generated would be theoretically enough to irrigate and fertilize millions of hectares of crops and to produce biogas to supply energy for millions of households (Mateo-Sagasta et al. 2015).

With regards to the city of Montes Claros (Minas Gerais, Brazil), currently, on average, 252 tons of sewage sludge are generated per month in the sewage treatment of the municipality, according to the Minas Gerais Sanitation Company (COPASA), with this waste ending at the sanitary landfill located inside the station. In reality, an increase of the production of sewage sludge is expected for the coming years. In fact, considering the growth of urban centers and the expansion of the public policy for sewage treatment the Federal Law of Brazil n. 14026 of 15 of July of 2020 (Legislative 2020) establishes that the local government must provide public services sanitation. Besides, it stipulates targets for the sewage collection that includes 90% of the population up to December of 2033. Therefore, it is crucial to adopt more efficient practices for the sludge produced from the sewage treatment plants. The circular-economy concept seems to be the solution, for instance, with the sewage sludge becoming a raw-material that partially replaces the clay mass in the production of ceramic materials.

The application of sewage sludge in the ceramic industry is a practice already used in several other countries and has positive advantages in reducing health risks. The ceramic industry appears to be widely favorable to receive industrial solid wastes, especially for absorbing new materials in the composition of its raw material (Araujo 2008). The main advantages are the stabilization of heavy metals in the ceramic matrix and elimination of pathogens in burns at high temperature phase (Romano et al. 2020). In addition, the constant production of industries combined with the high demand for ceramic products in the market, is shown as a favorable characteristic to the incorporation of the sewage sludge in the ceramic matrix as an alternative to waste disposal.

According to Montezuma Ceramic, which manufactures and sells bricks in the city of Montes Claros (Minas Gerais, Brazil), the factory has a burning capacity of two ovens and produces about 3000 tons of bricks, yearly. Recently, Cangussu *et al.* (Cangussu et al. 2021) carried out an exploratory study with the sewage sludge from the treatment plant of COPASA. The authors showed that this sludge could replace 10% of the clay materials in the production of solid bricks without losing important properties.

This paper advances the exploratory study carried out by Cangussu *et al.* (Cangussu et al. 2021) and aims to analyze the environmental impacts arising from the use of sludge from a Sewage Treatment Plant, through the Life Cycle Assessment tool. Here, three scenarios are replicated; with the environmental impacts of the solid bricks production with and without sewage sludge analyzed and compared. Life cycle assessment (LCA) is used as a tool to investigate environmental sustainability and can be explored to integrate with social and economic effects to quantify environmental impacts for energy generation from crop residues (Prasad et al. 2020). The tool is also used in others sectors of the economy (Sazdovski et al. 2021) and by researchers from all over the world (Christensen et al. 2020).

The transition towards a circular economy in the built environment is vital to reduce resource consumption, emissions and waste generation. To support the development of circular building components, assessment metrics are needed. Previous work identified LCA as an important method to analyze the environmental performance in a circular economy context (Jansen et al. 2020).

Taking into consideration the effects on the environment generated by the waste utilizations, the LCA methodology was applied. This tool is based on the study of environmental contributions to each stage of a product or system through analysis of quantitative inputs of energy and necessary inputs and waste outputs and emissions to the environment (Gutierrez 2014). Thus, LCA was applied to determine the benefits linked to environmental impacts and the use of resources in the use of these wastes, helping to make conclusions about the most appropriate end use sewage sludge.

2. Methodology: Life Cycle Assessment (LCA)

LCA approaches are internationally standardized tools used to assess impacts in production processes and are thus also suitable for the sustainability assessment of bio/eco-based products (Areias et al. 2020; D’Amato et al. 2020; Ramos Huarachi et al. 2020; Erdogmus et al. 2021; Zhang and Biswas 2021). LCA can provide valuable information for material selection, design and optimization by generating insight into environmental ‘pinch-points’, savings opportunities and trade-offs (Tapper et al. 2020).

The construction of the LCA was carried out considering the criteria and recommendations described in the standards ABNT NBR ISO 14040:2014 (ABNT 2014a) – “Environmental management – Life Cycle Assessment: Principles and Structure” and ABNT NBR ISO 14044:2014 (ABNT 2014b) – “Environmental management – Life Cycle Assessment: Requirements and Guidelines”. According to these standards, the LCA should contain in its structure four fundamental steps: the objective and scope; the analysis of inventory; the evaluating impact; and the interpretation (see Fig. 1).

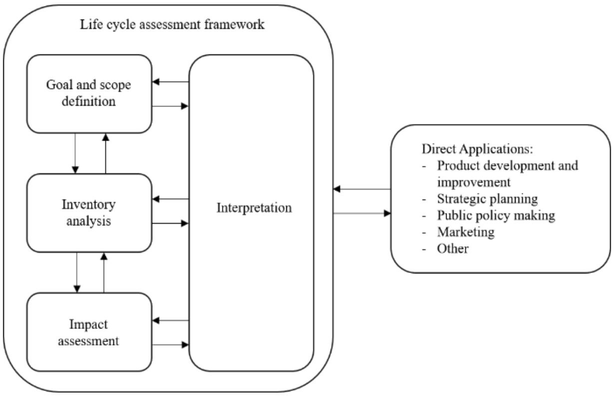

Fig. 1. Phases of an LCA.

For the definition the objective of the LCA, it was decided that the purpose of the research is to analyze the environmental impacts related to atmospheric emissions and depletion of natural resources in the ceramic brick production chain and compare the impacts observing the common production system (Scenario I) and the system using sewage sludge in the ceramic mass (Scenario II). Furthermore, the objective was to evaluate the environmental impacts on the production system of bricks with incorporation of sludge, assuming that diesel consumption would be equal to fuel consumption in common production (Scenario III).

The boundaries of the system were established considering the steps of extraction and obtaining the raw material, transport of clay and production of ceramic bricks, as represented by the dashed line in Fig. 2. As the study consisted of a simplified evaluation, based only on the production phases and not considering the final distribution of the product, only processes with greater contribution to the system were detailed and the study was classified as Cradle-to-gate. Cradle-to-gate assessments can be a useful basis from which to derive indicators for proposing mitigation actions for reducing environmental impacts from the production phase up to the packaging conversion process (Sazdovski et al. 2021).

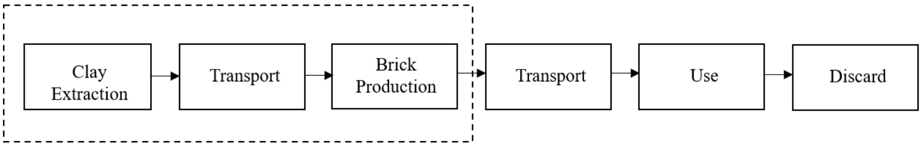

Fig. 2. System boundaries.

The unit functional (UF) was also defined as the input of 1 ton of ceramic material for burning in the three scenarios. According to ABNT NBR ISO 14040 (ABNT 2014a), it is necessary to determine this unit to ensure the possibility of comparing LCA results using a common basis. For the analysis of the LCA of the study, the OpenLCA software was used, as it is a free and open-access tool. The method adopted to assess the impacts was ReCiPe 2016, as it is a widely used method and deals with a midpoint approach, characterizing potential impacts to the environment. The inventoried data consists of raw material and energy inputs and outputs of atmospheric emissions and products. It used a free library available on the online platform of software, especially BioEnergieDat, of German origin, combined with the LCA methods package OpenLCA. In addition, other data applied in the survey that was not included in existing databases was collected from literature reviews on the production of ceramics and the generation of sewage sludge, including the geographic region of the study. For a better visualization of the individual contributions of each stage of the life cycle, Flow of Life Diagrams (FLD) were constructed indicating the inputs and outputs of each elementary process of the system, as shown in Fig. 3. The survey of inputs and outputs of each elementary process was done considering the unit functional and the flow was represented indicating the predecessor and successor process.

The characteristics of the bricks to be produced in the two scenarios were obtained from the exploratory research carried out by Cangussu *et al.* (Cangussu et al. 2021) which is in agreement with the data from the research of Silva (Silva 2016), both researches about the technical feasibility of incorporating sludge into red ceramics. According to the author, bricks with the addition of 10% of sludge in their total mass showed appropriate mechanical results and met the minimum requirements defined by current standards.

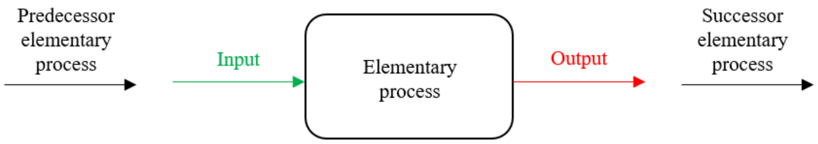

Fig. 3. Flow of Life Diagram (FLD).

Considering the unit functional of the present work, the extraction of 1.0 ton of clay was considered in Scenario I. In Scenarios II and III, considering the incorporation of 10% of dry sludge in the total mass, the amount of clay to be extracted was 0.9 ton.

According to the Ministry of Energy and Mines of Brazil (MME 2009), the average consumption of diesel for clay extraction in a captive mine is 0.80 liters per ton. Thus, in Scenario I the consumption of diesel for extraction of clay is 0.80 liters. However, in Scenarios II and III the consumption is 0.72 liters.

The atmospheric emission factors generated by clay extraction with a backhoe, based on the consumption in liters of diesel, is described in Table 1. The emissions of methane (CH_4) and nitrous oxide (N_2O) were calculated using the atmospheric emission factors of diesel burning in medium trucks (MMA 2013).

Table 1. Emission factors for mining machines - Backhoe.

CO_2 (g/L)	CO (g/L)	Nox (g/L)	SO_2 (g/L)	MP (g/L)
2466.2	15.5	38.5	0.8	5.8

Source: (Seye 2003).

The processes for obtaining and drying the sludge were not analyzed in the LCA, covering only the phase of transporting the material to the brick manufacturing industry in the life cycles of waste reuse scenarios.

In the transport flow of the extracted clay to the ceramics, a 5 km distance was assumed. In the stage of transporting the sludge from the Sewage Treatment Plant to the ceramic plant, a distance of 10 km was assumed, based on the real context. To calculate diesel consumption in each phase of transporting materials and emissions generated by burning the fuel, the National Inventory of Atmospheric Emissions by Road Motor Vehicles, launched in 2014 by the referred to Ministry of the Environment, was used. Transport flows were analyzed considering a mileage of 5.6 km per liter of diesel consumed, using a dump truck with a load of 13 000 kg.

Thus, for transporting a load of 1.0 ton of clay in Scenario I, there is a consumption of 0.0686 liters of diesel. On the other hand, to transport the load of 0.9 ton of clay in Scenario II, the consumption is 0.0618 liters. Also in this scenario, considering the transport of a load of 0.1 ton of sludge from the sewage treatment plant to the ceramic plant, the diesel consumption is 0.0137 liters.

In Scenario III, the diesel consumption is equal to the total consumption in Scenario I, which corresponds to 0.8686 liters. Thus, considering that the quantity of diesel required in the extraction of Scenario III is 0.72 liters and the transport of clay uses 0.0618 liters, the consumption of diesel in the transport of sludge is 0.0869 liters. Thus, in this scenario, the Sewage Treatment Plant is artificially located at a distance of 63.2 km from the brick production plant. Calculations of atmospheric emissions from burning diesel were made using pre-established factors as described in Table 2.

Table 2. Atmospheric emission factors for trucks with diesel engines.

CO_2 (kg/L)	CO (g/km)	NOx (g/km)	N_2O (g/km)	CH_4 (g/km)	HC[1] (g/km)	MP[2] (g/km)
2.603	2.856	5.74	0.168	3.36	0.0336	0.0392

[1] Non-methane hydrocarbons; [2] Particulate material

Source: Adapted from Ref. (MMA 2013).

To determine the production flow data of the bricks, the material burning step was considered only, considering that the other phases (homogenization, lamination and drying) are similar for the three analyzed systems. The furnace type adopted for the burning was Cedan, as the model present in the mentioned factory, with an energy yield of 409 kcal/kg and thermal efficiency of 54%, according to the manual Efficient Furnaces for the Red Ceramic Industry, launched in 2015 by the National Institute of Technology of Brazil (INT).

Eucalyptus sawdust is the energy source for burning used in the Montes Claros industry. However, considering that emissions from biomass burning depend on its state and composition, data referring to wood burning was adopted (FEAM, 2012), due to the lack of in-depth information on the sawdust used. The calorific value of the material is 3100 kcal/kg, according to the National Energy Balance based on the year 2019. The maximum firing temperature is 900 °C, and the furnace is gradually heated until reaching the final temperature and remaining stabilized. The atmospheric emission factors for the burning process are shown in Table 3.

Table 3. Atmospheric emission factors for the burning process.

MP (kg/ton)	SOx (kg/ton)	CO (kg/ton)	HC (kg/ton)
5.0	0.75	1.3	1.35

Source: FEAM (Ambiente et al. 2012).

One of the limitations in the development of the research consisted in the quantification of emissions data in the firing step of the ceramic pieces with sludge utilization. Areias (2015) concluded in his study that the incorporation of sewage sludge into red ceramics increases the porosity of the bricks, but also causes a decrease in energy expenditure during the burning stage due to the release of heat from the burning of organic matter. Due to the lack of available information on gas emissions in this process, these outputs were not considered in the elementary flow, proceeding only with an analysis of energy savings. The findings of this author (Areias 2015) were used in this study. Thus, the calorific power of the sewage sludge was assumed to contribute 1158 kcal per kg of sludge.

The effluent and waste output data from the brick production process were not added to the LCA, as they are not included in the objective of the study. In developing of the impact life cycle assessment (LCIA), defined categories of impact being evaluated were namely: global warming; formation of fine particles, mineral resources scarcity, photochemical ozone formation – effects on vegetation; photochemical ozone formation – effects on human health; destruction of stratospheric ozone; and terrestrial acidification. The categories were selected according to the objective of the LCA, considering those that are most addressed in studies related to the production of ceramic products and that are directly impacted by atmospheric emissions and consumption of natural resources.

In the interpretation stage, the results of the data inventory analysis and the impact assessment were verified to validate the conclusion of the LCA objective and generate recommendations on the analyzed systems.

3. Results and Discussions

The three analyzed scenarios used the OpenLCA considering each chain process flows shown in Fig. 4 and Fig. 5. In the sludge transport process, represented in Fig. 6, the input consists of diesel consumption and the outputs were the atmospheric emissions from transport and the quantity of sludge transported, according to the quantities described in Table 4. The elementary sludge transport process was considered only in the life cycles of systems with waste recovery (Scenário II and III). For the clay extraction process, the FLD built was the same for the three scenarios, with energy inputs and emission outputs and the clay itself, according to Fig. 7. However, the resulting quantities have variations, as shown in Table 5.

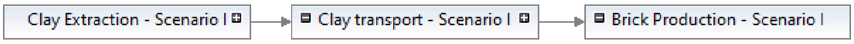

Fig. 4. Modeling Scenario I.

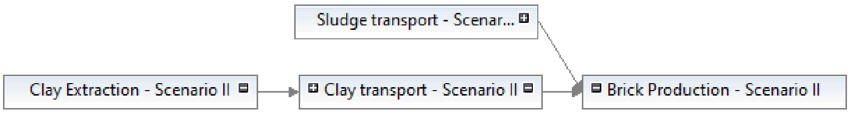

Fig. 5. Modeling Scenario II and III.

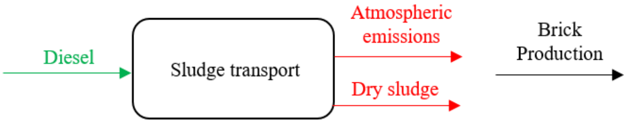

Fig. 6. FLD of the sludge transport process.

Table 4. Inputs and outputs of the sludge transport process.

Scenario	Appetizer	Departures							
	Energy	Atmospheric Emissions							By-product
	Diesel Oil (L)	CO_2 (kg)	CO (g)	NO_x (g)	N_2O (g)	CH_4 (g)	HC (g)	MP (g)	Dried Sludge (ton)
II	0.0137	0.036	0.039	0.079	0.002	0.046	0.0005	0.0005	0.1
III	0.0869	0.226	0.248	0.499	0.015	0.292	0.0029	0.0034	0.1

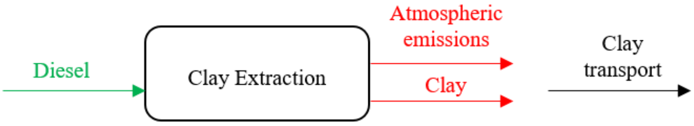

Fig. 7. FLD of the clay extraction process.

Table 5. Inputs and outputs of the clay extraction process.

Scenario	Input	Output						
	Energy	Atmospheric emissions						By-product
	Diesel oil (l)	CO_2 (kg)	CO (g)	Nox (g)	SO_2 (g)	CH_4 (g)	MP (g)	Clay (g)
Scenario I	0.800	1.97	12.40	30.80	0.640	2.69	0.134	4.64
Scenario II	0.720	1.77	11.16	27.72	0.576	2.45	0.121	4.18
Scenario III	0.720	1.77	11.16	27.72	0.576	2.45	0.121	4.18

The FLD of the clay transport process to the brick production area was elaborated considering the input of fuel and the output of atmospheric emissions, represented by Fig. 8. The quantities are arranged in Table 6. The FLD of the brick production was determined considering the inputs and outputs related to the burning process of the material, as shown in Fig. 9.

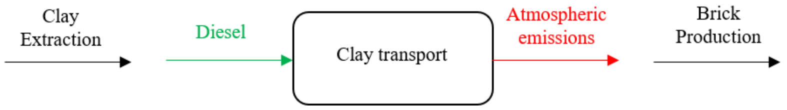

Fig. 8. FLD of the clay transport process.

Table 6. Inputs and outputs of the clay transport process.

Scenario	Input	Output						
	Energy	Atmospheric emissions						
	Diesel oil (g)	CO_2 (kg)	CO (g)	Nox (g)	N_2O (g)	CH_4 (g)	HC (g)	MP (g)
Scenario I	0.0686	0.18	0.196	0.394	0.012	0.231	0.0023	0.0027
Scenario II	0.0618	0.16	0.177	0.355	0.010	0.208	0.0021	0.024
Scenario III	0.0618	0.16	0.177	0.355	0.010	0.208	0.0021	0.024

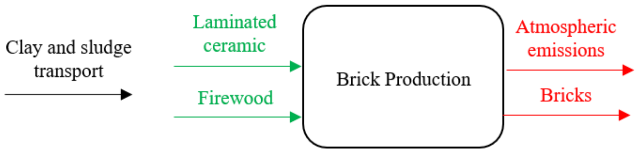

Fig. 9. FLD of the brick production process.

With regards to the energy analysis, as calculations performed by Areias (2015) seeking to evaluate the energy savings of biomass caused by the incorporation of sewage sludge in the production of bricks.

Considering that the specific consumption of the Cedan kiln is 409 000 kcal/ton and the thermal efficiency is 54%, the energy demand for burning 1.0 ton of the ceramic product is 757 407 kcal. Since the calorific value of firewood is 3100 kcal/kg, the required consumption of firewood is 244.33 kg.

In Scenarios II and III, with the use of 10% of the sewage sludge in the mass of the ceramic matrix, a total quantity of 0.1 ton of waste is incorporated. Thus, considering the calorific power of the sewage sludge as 1158 kcal/kg, it results in a supply of 115 800 kcal for the residue. Assessing the yield of waste in relation to total consumption, which corresponds to 757 407 kcal, results in energy savings of approximately 15.29%. Thus, taking into account the use of all the heat generated within the bricks by the sewage sludge, the incorporation of the sewage sludge in the ceramic causes a yield in relation to firewood of 37.35 kg. Another study (Girondi et al. 2020) investigated the use of cigarette waste in ceramic mixtures at mass ratios of 0%, 2.5%, 5%, 7.5% and 10%, and concluded that exothermic peaks occur in the mixture with 10% cigarette waste. To calculate the output of brick mass after burning in the systems, the loss of mass to fire was considered. Here, the loss of mass was estimated based on finding of Ref. (Silva 2016). Thus, for the loss of mass to fire, in Scenario I a percentage of 9.47% was adopted. As there is an increase in the loss of mass to fire in bricks using the sludge, for the loss of mass to fire, in Scenarios II and III a percentage of 16.8% was adopted.

In Scenario I, with 9.47% of mass loss, the final quantity produced is 0.905 tons, while, in Scenarios II and III, whose mass loss is 16.8%, the final production corresponds to 0.832 ton of bricks. In this sense, based on the apparent post-firing specific mass, the resulting quantities from the burning process for each scenario were described in Table 7. With the quantitative data from each stage of the analyzed systems, the software was launched and the life cycle impact assessment report was generated for the previously defined impact categories. The results of each category in the two analyzed scenarios, according to the impact factors of the ReCiPe 2016 method, are shown in Table 8.

Table 7. Inputs and outputs of the brick production process.

Scenario	Input	Output						
	Energy	By-product		Atmospheric emissions*				Product
	Firewood (kg)	Clay (t)	Sludge (t)	SO (kg)	CO (kg)	MP (kg)	HC (kg)	Bricks (t)
Scenario I	244.33	1.0	-	0.183	0.32	1.22	0.33	0.905
Scenario II	206.98	0.9	0.1	0.155	0.27	1.03	0.28	0.832
Scenario III	206.98	0.9	0.1	0.155	0.27	1.03	0.28	0.832

The comparison of the results of each impact category between Scenarios I, II and III can be better visualized through the graph represented in Fig. 10. The graph presents the results according to the relative percentages of impacts generated in each scenario. Thus, for each impact category, the maximum result is defined as 100% and the impacts generated in the other scenarios are represented as a percentage of this result. Fig. 11 to Fig. 16 presents the individual influence of each elementary process on the total impacts generated in each category in Scenarios I, II and III.

Table 8. Results of the Life Cycle Impact Assessment by the ReCiPe method 2016.

Category Impact	Scenario I	Scenario II	Scenario III	Unit
Terrestrial acidification	1.95114e-1	1.65939e-1	1.66090e-1	kg SO_2 eq
Global warming	2.29446e+0	2.10302e+0	2.30540e+0	kg CO_2 eq
Stratospheric ozone depletion	1.60532e-6	1.47018e-6	1.60532e-6	kg CFC_{11} eq
Shortage of mineral resources	1.04000e+1	9.36000e+0	9.36000e+0	kg Cu eq
Photochemical ozone formation, effects on human health	3.11942e-2	2.81537e-2	2.85734e-2	kg NO_x eq
Photochemical ozone formation, effects on vegetation	3.11942e-2	2.81537e-2	2.85734e-2	kg NO_x eq
Fine particle formation	5.67576e-2	4.82799e-2	4.83261e-2	kg $PM_{2.5}$ eq

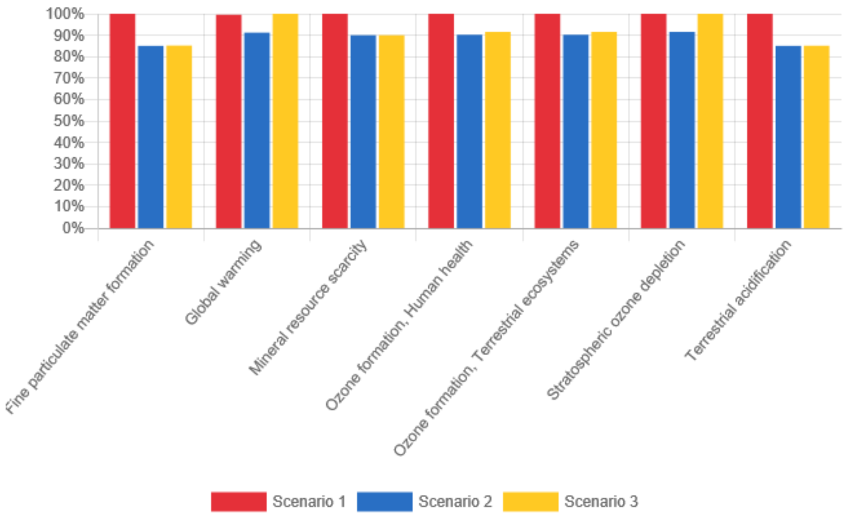

Fig. 10. Representation of the relative percentages of impacts generate.

Considering terrestrial acidification and the formation of fine particles, there was a reduction of approximately 15% of the effects generated in Scenarios II and III, with the use of sludge in the production of bricks, compared to production without incorporation of sludge. In the category of scarcity of mineral resources, there was, on average, a 10% decrease in potential impacts in Scenarios II and III. Regarding the formation of photochemical ozone (effects on human health and vegetation), the impacts were reduced by 10% in Scenario II and 8% in Scenario III. Considering the categories of global warming and stratospheric ozone depletion, in Scenario II there was a 9% reduction in the impacts caused. However, Scenario III presented similar results in these categories to Scenario I.

Another study, using ornamental stone waste in ceramic parts, also concluded that the incorporation of waste material alleviates environmental impacts in general, contributing to the reduction of the use of clay as raw material in the production of ceramic parts, contributing to the sustainability of industrial activity. The study points out as the main result, the reduction of 35.74% of the impacts related to the category of the emission of greenhouse gases, and scarcity of mineral resources, 14.83% reduction (Barbosa et al. 2021).

A study carried out in China, performance various options combining sludge treatment technologies and disposal schemes using LCA. The authors investigated six scenarios involving various sludge treatment technologies and disposal strategies: landfilling (S1), mono-incineration (S2), co-incineration (S3), brick manufacturing (S4), cement manufacturing (S5), and fertilizer for urban greening (S6). The results indicate that S2 has the best Greenhouse Gas (GHG) performance, followed by S4. The substitution rate for the brick manufacturing (S4) was 10% and they observed that the material offset is equivalent to the emissions avoided during stone mining and quarrying as well as in the transportation stages of the corresponding raw materials required for brick/cement manufacturing. Based on the life cycle inventory analysis, the GHG emissions, the S2 was in the second position. Also, the energy recovery offsets in S4 was very large (50.9%), thus resulting in good Global Warming Potential (GWP) performance. The carbon sequestration could significantly improve the GHG performance of S6, which may nearly become the second best (S4) scenario (Liu et al. 2013).

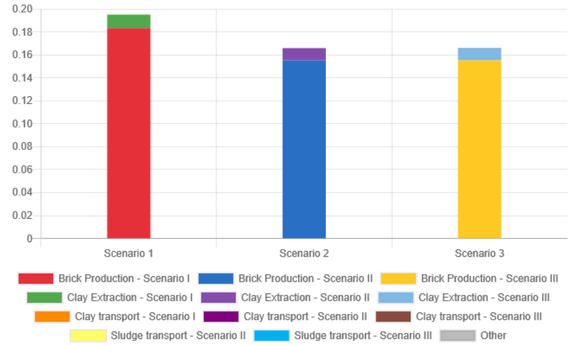

Fig. 11. Impacts of terrestrial acidification (kg SO² eq).

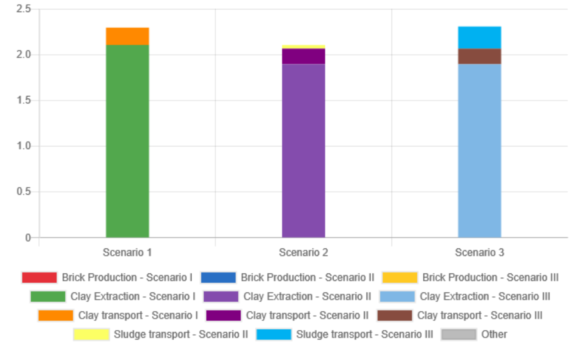

Fig. 12. Global warming impacts (kg CO²eq).

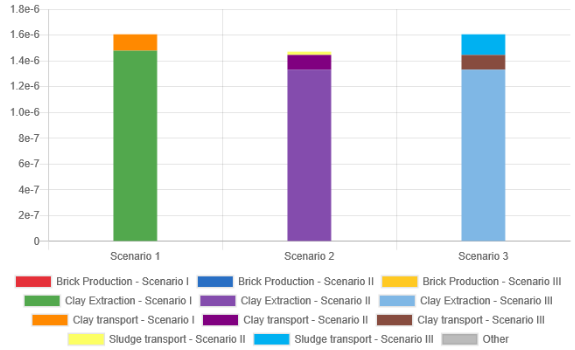

Fig. 13. Impacts of stratospheric ozone destruction (kg CFC11eq).

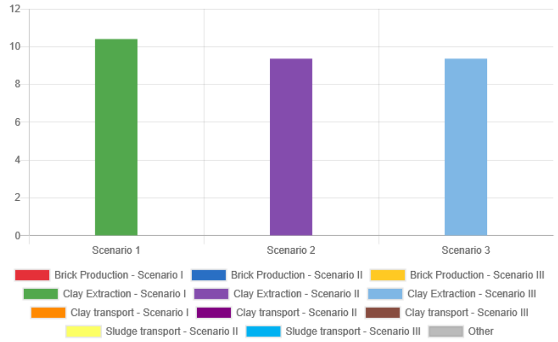

Fig. 14. Impact and scarcity of mineral resources (kg Cu eq).

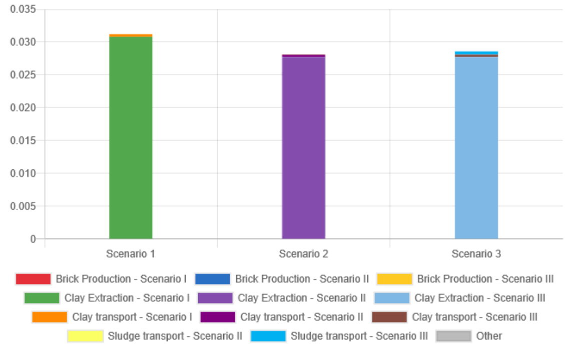

Fig. 15. Impacts formation of photochemical ozone effects on human health and vegetation (kg NOx eq).

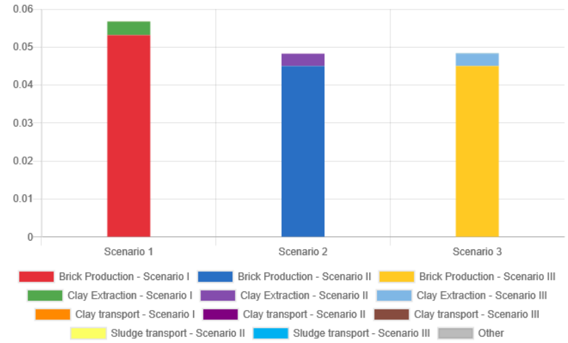

Fig. 16. Formation of fine particles (kg PM2.5 eq).

Comparing the Scenarios I and III wherein the consumption of diesel was the same (due to in Scenarios III the sewage treatment plant was artificially placed at the distance of 63.2 km from the ceramic plant), it is observed that the incorporation of 10% of sewage sludge still has several environmental benefits because it reduces all the environmental impacts apart from the ones controlled by the diesel consumption.

4. Final Remarks and Conclusions

Previous studies wherein the replacement of 10% of clay by sewage sludge demonstrated that the properties of solids bricks were not negatively affected. Here, the corresponding environmental benefits were evaluated based on the life cycle assessment methodology. Based on the results obtained by applying the life cycle assessment methodology, it was possible to conclude that the production process of ceramic bricks with the incorporation of sewage sludge causes less environmental impacts in several impact categories. With the replacement of 10% of the sewage sludge in the mass of the ceramic matrix the following findings were found:

- Energy efficiency is improved with energy savings of approximately 15%.
- Reduction of approximately 15% of the effects generated in the terrestrial acidification and in the formation of fine particles.
- Circa 10% decrease in the potential impacts in the scarcity of mineral resources.
- The impacts in formation of photochemical ozone was decreased by 10% in Scenario II and 8% in Scenario III.

It is noteworthy that the results obtained through the life cycle assessment represent potential impacts, not precisely translating the actual impacts caused, as these are correlated with particular characteristics of the affected regions. More studies are necessary, among others, the authors highlight the need to study the atmospheric contributions generated by the handling and burning of the sludge during the production of ceramic materials and during the thermal drying of the waste in the sewage treatment plant. Also to evaluate the waste disposal life cycle in landfill and analyze the costs of the processes, in order to expand the study scenarios and obtain more data for decision-making on the best disposal of the waste.

Acknowledgments

The authors are grateful to the State University of Montes Claros (UNIMONTES). This work is financially supported by: Base Funding – UIDB/04708/2020 of the CONSTRUCT – Instituto de I&D em Estruturas e Construções - funded by national funds through the FCT/MCTES (PIDDAC). This work is funded by national funds through FCT – Fundação para a Ciência e a Tecnologia, I.P., under the Scientific Employment Stimulus – Institutional Call – CEECINST/00049/2018.

Ethical Approval

Not applicable

Consent to Participate

Not applicable

Consent to Publish

Not applicable

Authors Contributions

Nara Cangussu – Data curation, Formal analysis, Investigation, Funding acquisition, Methodology, Resources, Writing – original draft, Visualization

Luana Vasconcelos – Formal analysis, Investigation

Lino Maia – Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing

Competing Interests

The authors declare that they have no competing interests

Availability of data and materials

Not applicable

References

ABNT (2014a) NBR ISO 14040: Environmental management - Life cycle assessment - Principles and structure / Gestão ambiental - Avaliação do ciclo de vida - Princípios e estrutura (avaiable only in Portuguese)

ABNT (2014b) NBR ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines. / Gestão ambiental - Avaliação do ciclo de vida - Requisitos e orientações (avaiable only in portuguese).

Ambiente M, Sustent D, Diretoria MA, Ger D (2012) Energy Assessment of Red Ceramic Industries in the State of Minas Gerais / Avaliação Energética das Indústrias de Cerâmica Vermelha no Estado de Minas Gerais (avaiable only in Portuguese)

Araujo F da SD de (2008) Influence of ETE sludge on the mass for the manufacture of red ceramics / Influência do lodo de ETE na massa para fabricação de cerâmica vermelha

Areias IOR (2015) Incorporation of sludge from the Sewage Treatment Plant (ETE) in Campos dos Goytacazes-RJ in red ceramic / Incorporação de lodo da Estação de Tratamento de Esgoto (ETE) do município de Campos dos Goytacazes-RJ em cerâmica vermelha. Universidade Estadual do Norte Fluminense Darcy Ribeiro, Brazil.

Areias IOR, Vieira CMF, Colorado HA, et al (2020) Could city sewage sludge be directly used into clay bricks for building construction? A comprehensive case study from Brazil. J Build Eng 31:101374. https://doi.org/https://doi.org/10.1016/j.jobe.2020.101374

Azevedo ARG de, Marvila MT, Rocha HA, et al (2020) Use of glass polishing waste in the development of ecological ceramic roof tiles by the geopolymerization process. Int J Appl Ceram Technol 17:2649–2658. https://doi.org/https://doi.org/10.1111/ijac.13585

Barbosa MZ, de Oliveira Dias J, Marvila MT, de Azevedo ARG (2021) Life cycle approach applied to the production of ceramic materials incorporated with ornamental stone wastes. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-021-16386-w

Cangussu N, Silva L, Maia L (2021) Incorporation of the sludge of sewage treatment plant on ceramic bricks manufacture: an exploratory study. Submitt to J UPorto J Eng ISSN 2183-6493; Status Recomm Publ after Revis

Christensen TH, Damgaard A, Levis J, et al (2020) Application of LCA modelling in integrated waste management. Waste Manag 118:313–322. https://doi.org/10.1016/j.wasman.2020.08.034

CNMA (2021) CONAMA Resolution Nº 498. National Council for the Environment, Brazil.

CNMA (2006) CONAMA Resolution Nº 375. National Council for the Environment, Brazil.

D’Amato D, Gaio M, Semenzin E (2020) A review of LCA assessments of forest-based bioeconomy products and processes under an ecosystem services perspective. Sci Total Environ 706:135859. https://doi.org/10.1016/j.scitotenv.2019.135859

Duarte ACL (2008) Incorporation of sewage sludge into the ceamic mass for the manufacture of solid bricks: An alternative for the final disposal of waste (avaiable only in Portuguese). Universidade Federal do Rio Grande do Norte, Brazil.

Erdogmus E, Harja M, Gencel O, et al (2021) New construction materials synthesized from water treatment sludge and fired clay brick wastes. J Build Eng 42:102471. https://doi.org/https://doi.org/10.1016/j.jobe.2021.102471

França Junior AT de (2008) Analysis of the Energy Use of Biogas Produced in a Sewage Treatment Plant / Análise do Aproveitamento Energético do Biogás Produzido numa Estação de Tratamento de Esgoto Antonio Tavares de França Junior. Planta

Gencel O, Kazmi SMS, Munir MJ, et al (2021) Feasibility of using clay-free bricks manufactured from water treatment sludge, glass, and marble wastes: An exploratory study. Constr Build Mater 298:123843. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.123843

Girondi GD, Marvila MM, de Azevedo ARG, et al (2020) Recycling potential of powdered cigarette waste in the development of ceramic materials. J Mater Cycles Waste Manag 22:1672–1681. https://doi.org/10.1007/s10163-020-01058-7

Gutierrez KG (2014) Analysis and management of environmental impacts in the treatment of domestic sewage through life cycle assessment / Análise e gerenciamento de impactos ambientais no tratamento de esgoto doméstico mediante avaliação de ciclo de vida. Universidade Federal de Minas Gerais, Brazil.

Jansen BW, Stijn A Van, Gruis V, Bortel G Van (2020) Resources , Conservation & Recycling A circular economy life cycle costing model (CE-LCC) for building components. Resour Conserv Recycl 161:104857.

https://doi.org/10.1016/j.resconrec.2021.105683

Jianu NR, Moga IC, Pricop F, Chivoiu A (2018) Wastewater Sludge Used as Material for Bricks Fabrication. IOP Conf Ser Mater Sci Eng 374:8–13. https://doi.org/10.1088/1757-899X/374/1/012061

Joo-Hwa T (1987) Bricks Manufactured from Sludge. J Environ Eng 113:278–284. https://doi.org/10.1061/(ASCE)0733-9372(1987)113:2(278)

Kadir AA, Rahim ASA (2014) An Overview of Sludge Utilization into Fired Clay Brick. Int J Environ Ecol Geol Mar Eng 8:528–532

Keerthana S, Kavya K, Pradeep T, Sharmila S (2019) Study on effect of partial replacement of sludge in bricks. Int J Recent Technol Eng 7:364–369

Kioupis D, Skaropoulou A, Tsivilis S, Kakali G (2018) The application of experimental design models in order to optimize the synthesis of geopolymers. MATEC Web Conf 149:. https://doi.org/10.1051/matecconf/201714901029

Legislative (2020) Federal Law Nº 14.026. Official Diary of the Union, Brazil

Limami H, Manssouri I, Cherkaoui K, Khaldoun A (2021) Recycled wastewater treatment plant sludge as a construction material additive to ecological lightweight earth bricks. Clean Eng Technol 2:100050. https://doi.org/https://doi.org/10.1016/j.clet.2021.100050

Liu B, Wei Q, Zhang B, Bi J (2013) Life cycle GHG emissions of sewage sludge treatment and disposal options in Tai Lake Watershed, China. Sci Total Environ 447:361–369. https://doi.org/10.1016/j.scitotenv.2013.01.019

Mateo-Sagasta J, Raschid-Sally L, Thebo A (2015) Global Wastewater and Sludge Production, Treatment and Use. In: Wastewater. Springer, Dordrecht, Dordrecht

Mendes BC, Pedroti LG, Fontes MPF, et al (2019) Technical and environmental assessment of the incorporation of iron ore tailings in construction clay bricks. Constr Build Mater 227:116669. https://doi.org/10.1016/j.conbuildmat.2019.08.050

Minh Trang NT, Dao Ho NA, Babel S (2021) Reuse of waste sludge from water treatment plants and fly ash for manufacturing of adobe bricks. Chemosphere 284:131367. https://doi.org/https://doi.org/10.1016/j.chemosphere.2021.131367

MMA (2013) National inventory of atmospheric emissions by road motor vehicles / Inventário nacional de emissões atmosféricas por veículos automotores rodoviários

MME (2009) Clay profile for Red Ceramics / Perfil de argilas para Cerâmica Vermelha. Ministério Minas e Energ. 30

Okuno N, Takahashi S (1997) Full scale application of manufacturing bricks from sewage. Water Sci Technol 36:243–250. https://doi.org/https://doi.org/10.1016/S0273-1223(97)00686-0

Prasad S, Singh A, Korres NE, et al (2020) Sustainable utilization of crop residues for energy generation: A life cycle assessment (LCA) perspective. Bioresour Technol 303:122964.

https://doi.org/10.1016/j.biortech.2020.122964

Ramos Huarachi DA, Gonçalves G, de Francisco AC, et al (2020) Life cycle assessment of traditional and alternative bricks: A review. Environ Impact Assess Rev 80:106335. https://doi.org/https://doi.org/10.1016/j.eiar.2019.106335

Romano M, Pelozo G, Quaranta N, et al (2020) Ceramic matrices for immobilization of heavy metals adsorbed on rice husk. SN Appl Sci 2:1–9. https://doi.org/10.1007/s42452-020-2767-3

Sazdovski I, Bala A, Fullana-i-Palmer P (2021) Linking LCA literature with circular economy value creation: A review on beverage packaging. Sci Total Environ 771:145322. https://doi.org/10.1016/j.scitotenv.2021.145322

Seye O (2003) Life cycle analysis applied to the production process of structural ceramics using Capim Elefante as energy input / Análise de ciclo de vida aplicada ao processo produtivo de cerâmica estrutural tendo como insumo energético Capim Elefante. Universidade Estadual de Campinas, Brazil.

Silva LM (2016) Study of the technical feasibility of incorporating red ceramic sewage treatment plant sludge for brick production / Estudo da viabilidade técnica da incorporação do lodo de estação de tratamento de esgoto em cerâmica vermelha para produção de tijolos. Universidade Estadual de Montes Claros, Brazil.

Tapper RJ, Longana ML, Norton A, et al (2020) An evaluation of life cycle assessment and its application to the closed-loop recycling of carbon fibre reinforced polymers. Compos Part B Eng 184:107665. https://doi.org/10.1016/j.compositesb.2019.107665

Weng C-H, Lin D-F, Chiang P-C (2003) Utilization of sludge as brick materials. Adv Environ Res 7:679–685. https://doi.org/https://doi.org/10.1016/S1093-0191(02)00037-0

Zat T, Bandieira M, Sattler N, et al (2021) Potential re-use of sewage sludge as a raw material in the production of eco-friendly bricks. J Environ Manage 297:113238. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.113238

Zhang X, Biswas WK (2021) Development of eco-efficient bricks – A life cycle assessment approach. J Build Eng 42:102429. https://doi.org/https://doi.org/10.1016/j.jobe.2021.102429