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Life cycle assessment of eco-brick production using PET particle reinforced epoxy resin composites

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Abstract The process of urbanisation contributes to the growth of waste generation and causes environmental pollution. One of the most common plastic waste is polyethylene terephthalate (PET). This plastic waste is often used as mixed material in construction. The use of life-cycle assessment (LCA) is a possible tool to assess the sustainability of a product in the long term. After analysing the latest literature, it was found that the study of PET waste in building materials is one of the sustainable alternatives for waste reduction. This research contributes to the improvement of sustainability in alternative building materials through LCA. A gate-to-gate approach is adopted in this research. LCA Calculations for the production of eco-bricks were carried out in accordance with ISO 14044. GaBi software was used to identify and quantify impacts within the system boundaries. The calculations were based on the EDIP 2003 method for assessing impacts. The results show that the use of epoxy resin and PET as raw materials for eco-tiles has an impact on ozone formation (OF) of 118 m2 UES*ppm*hours, which is due to the use of epoxy resin chemicals as adhesives in the production of eco-bricks. Eco-bricks made of PET and epoxy resin have better compressive strength than other materials. The addition of epoxy resin adhesive can increase the compressive strength of the eco-bricks by 50%. Despite the advantages of using epoxy resin and PET in eco-bricks, there are many uncertainties about their environmental impact. It can be concluded that the use of epoxy resin and PET particles in the production of eco-bricks does not pose excessive environmental risks and their use as alternative mixtures for the production of eco-bricks does not lead to a significant reduction in the environmental profile.

Keywords: LCA, eco-brick, epoxy resin, PET

1. Introduction

The demand for building and construction materials is increasing with the growth of the world's population. One of the raw materials used for building materials is brick. The increase in brick production in the world is taking place in different regions such as China, India, Canada, and Indonesia (More et al 2014; Nichols and Roachanakanan 2015). The increase in brick production will lead to a decrease in the natural resources of fertile clay that can only be used for brick production in the world. The addition of natural materials for construction will lead to the rapid depletion of natural resources. In addition, about 7 % of the world's total energy is consumed in the extraction, processing, and handling of raw materials for concrete production (Hossain et al 2020). Therefore, the use of various wastes in the production of bricks is important for a sustainable product.

Recycling is one way to reduce the environmental damage caused by large amounts of waste. Mixing plastic waste with soil to make bricks is one of the alternatives to recycling plastic waste. Using plastic waste in the construction of buildings is now a trend to achieve sustainability. In addition, adding plastic to concrete mixes can improve the properties of the product (Akinyele, Igba, Ayorinde, et al 2020; Gregori et al 2022; Mahdaoui et al 2021; Muñoz et al 2019; Rashid et al 2019). One form of recycling plastic waste is the production of eco-bricks. This eco-brick is a form of innovation to recycle plastic waste into building materials. Eco-bricks are produced without a drying process, so they have no impact on the environment. This is in contrast to the combustion process that takes place when bricks are manufactured.

Burning bricks emit about 70 to 282 g of carbon dioxide, 0.001 to 0.29 g of soot, 0.2 9 to 5.78 g of carbon monoxide (CO), and 0.15 to 1.56 g of particulate matter per kilogramme of brick burnt. In addition, the production of bricks consumes about 0.54 to 3.14 MJ of specific energy per kilogramme of bricks produced (Barros et al 2020). Therefore, it is necessary to produce environmentally friendly bricks by eliminating the burning process. The production of bricks without burning will help to reduce carbon dioxide emissions.

The sustainability of eco-bricks is closely related to their materials. This is because the choice of materials and the production process of eco-bricks account for a much larger share of the environmental impact in life cycle assessments (Zhao and Yang 2023). In recent years, the assessment and control of carbon emissions have become a fundamental strategy for

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sustainable development. A total of 37 industrialised countries have ratified the Kyoto Protocol, committing to reduce greenhouse gas emissions by 18% (Ahmed and Tsavdaridis 2018). Greenhouse gas emissions attract many researchers involved in environmental impact assessment, but greenhouse gas emissions are one of the parameters that need to be considered in environmental impact assessment. Other parameters that need to be considered in assessing environmental impacts are ozone depletion, water consumption, toxicity, eurofication and also resource depletion (Askham 2011; Bakalár et al 2021).

Life cycle assessment (LCA) is the most recognised and globally accepted method for evaluating and comparing the environmental impacts of processes and assessing their sustainability from raw materials to finished products (Yue et al 2022). LCA is a methodology for assessing the environmental impacts of processes and products throughout their life cycle. The assessment covers the entire life cycle of a product, process, or system, including the extraction and processing of raw materials, manufacturing, transport and distribution, as well as use, reuse, maintenance, recycling, and final disposal. Due to its integrated approach to framework, impact assessment and data quality, LCA has become a widely used method (Khasreen et al 2009).

The LCA method assesses the total resource use and pollutant emissions associated with the life cycle, such as raw material processing, final disposal, and recycling processes. Currently, LCA is well-developed and standardised. In the study, the LCA method was used to assess the environmental impacts associated with this type of eco-brick by defining and quantifying the energy and materials used and the environmental waste generated and evaluating the potential environmental impacts. The performance evaluation of plastic waste eco-bricks can comprehensively consider the environmental impacts and energy consumption, which can provide new ideas for the synergistic application of recycled plastic waste products. The scope of this LCA investigation is gate to gate", which is the shortest scope of a life cycle analysis, as only the activities most closely related to the production phase process are investigated.

Gate-to-gate in life cycle analysis is the analysis of the environmental impact of a product from the beginning of the production process to the finished product. It includes the stages before manufacturing, manufacturing, and post-manufacturing. It does not include the use of the product or its disposal. It is used to identify and quantify the potential environmental impacts of a product and to assist in the design process to reduce environmental impacts. It can also be used to compare the environmental impacts of different products or production methods.

Many studies have been conducted to assess the environmental impact of plastic waste mixtures in building materials. In research (Ahmed and Tsavdaridis 2018) analyzed LCA related to lightweight composite. In research (Zhao and Yang 2022; Zhang and Biswas 2021; La Rosa et al 2016) also analyzed LCA related to recycled materials in buildings. Research related to eco efficient brick and recycled and natural aggregate concrete was also investigated by (Zhang and Biswas 2021; Pradhan et al 2019). However, no studies of LCA have been conducted for modified eco-bricks with a mixture of PET particles and epoxy resin

This study aims to evaluate the environmental impact of using eco-bricks modified with a mixture of PET particles and epoxy resin and to analyse the environmental impact from a life cycle perspective that can be used to develop alternative sustainable building materials. This eco-brick is made of epoxy resin and PET particles. The main raw materials include epoxy resin and PET particles. In addition, this eco-brick has different types of resource consumption and therefore needs to be considered in order to reduce the impact on the environment and resources. These findings can be used by decision makers in the construction industry to develop sustainable construction policies.

2. Materials and Methods

2.1. Goal and scope definition

The aim of LCA in this research is to analyse the environmental impact of the production process of eco-bricks mixed with PET particles and epoxy resin throughout the production process. Based on the LCA results, suggestions are made for technological processes that can improve the environmental impact of the production process of eco-bricks.

2.2. Functional Unit

In this study, the functional unit (FU) is an important unit to evaluate the production system and compare it with different production systems. The functional units considered in this study are volume and weight, which are adopted from previous studies on the LCA of building materials. The functional unit used in this study is 1 m^3 Eco-brick block. In this study, the selected block has dimensions of 200x200x400 mm. Based on the optimisation results performed, the optimum composition ratio (A) is 89.9759%, the optimum particle size (B) is 1.14235 mm, and the curing time (C) is 6.97229 days. The result is a compressive strength of 44.1193 MPa, which has the most desirable properties. This shows that the strength of the mixture between the epoxy resin and the particles of PET gives a higher strength than an eco-brick made of a bottle filled with plastic. The functional unit determined in this study was an eco-brick weighing 1 kg.

The pre-determined functional unit starts from all raw materials, including production, to the finished product. In this study, only the production process of the eco-brick is considered. Some of the reasons for limiting this system are that raw material production is reported to be the biggest environmental impact on a building. The size and nature of the Eco-bricks are identical, so it is assumed that there are no significantly different subsequent processes, so consumption and emissions are the same. In this study, 3 scenarios are described in the Table 1.

Table 1 Scenario of study.

Scenario Name	Description
Scenario 1	Polyethylene terephthalate granulate (PET) and Epoxy resin
Scenario 2	Polyethylene terephthalate granulate (PET) and Clay
Scenario 3	Polyethylene terephthalate granulate (PET) and Cemen

2.3. System Boundaries

The choice of system boundaries and the parameters that go into the life cycle inventory is very influential and should be related to the objectives of the study. Furthermore, the system boundary will influence the final results of the study in addition to the interpretation (Lundin et al 2000; U et al 1997). The objective of this study is basically to quantify the environmental impacts of different flexible pavement layers. Basically, the life cycle of flexible pavements consists of several phases, namely the design of the pavement, the production of the raw material, the production of the asphalt mixture, the transport, the construction of the pavement, the use, and the end of life. The system boundary chosen in this analysis is "gate to gate". The environmental impacts caused by transport and the end-of-life phase are ignored, so only the production of raw materials and the manufacture of eco-bricks from a mixture of PET particles and epoxy resin are considered in this LCA study. The system boundary for the production of eco-bricks is shown in Figure 1.

The life cycle assessment study (LCA) is divided into four phases: Definition of objectives and scope, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Assessment (LCIA), and Life Cycle Interpretation. This section defines and explains the function of each phase of an LCA.

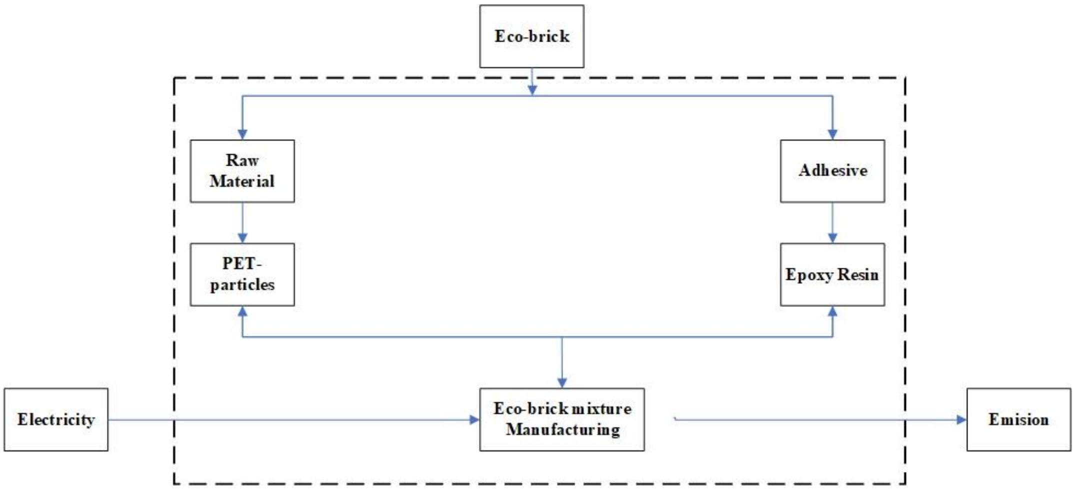

Figure 1 System boundaries of this research.

2.4. Assumption and limitation

The conduct of an LCA study is highly dependent on the availability of data and the way the study is conducted. It is important to assess the availability of data, the time needed to conduct the study, and also the financial resources. The following assumptions and limitations apply to this study:

- Environmental impacts are caused only by the main process, namely the production of eco-bricks.
- Environmental impacts related to the transport of raw materials are not considered.
- Environmental impacts related to the construction of the plant, associated machinery, and electrical installations are ignored, so only the impacts of the process of bolting a mixture of epoxy resin and PET particles into eco-bricks are analysed in this study.

2.5. Life Cycle Inventory (LCI)

In general, data are collected from a variety of sources that may not match the functional units of this study and therefore need to be adapted to meet the objectives of this study. This section consists of a full characterisation of the LCA input data used to develop the system for the different alternative eco-brick mix products. The data is then analysed using Gabi software. Gabi software is a commercial tool for modelling, calculating, and visualising material and energy flow systems. It is used to analyse the process flows throughout the product life cycle.

2.6. Life Cycle Impact Assessment (LCIA)

The LCI stage shows the environmental data for the production process of the eco-brick mix, which consists of environmental impacts such as raw material consumption, air and water emissions, etc. This stage can be used to estimate the number of pollutants indicated for each stage without knowing the associated potential environmental damage.

The LCIA approach is used to compare the environmental impacts measured in the LCI stage. LCIA consists of several components: Classification, Characterisation, Normalisation, and Weighting.

The exposure categories selected in this study are listed in Table 2. This category shows the environmental impacts of the manufacturing process of the eco-brick mix and depends on the method chosen. EDIP 2003 is the more appropriate method for the purpose and scope of this study. The EDIP 2003 method is a form of assessment method in LCA. In addition, the EDIP 2003 method can also estimate impact categories related to waste (Tabatabaei et al 2021).

Table 2 Impact categories.

Impact Category	Units	LCIA Methods
GWP – Global Warming Potential	kg CO2 eq	EDIP 2003
AP - Acidification Potential	m2 UES	EDIP 2003
POF - Photochemical ozone formation (impact on human health and materials)	pers*ppm*hours	EDIP 2003
OF- ozone formation (impact on vegetable)	m2 UES*ppm*hours	EDIP 2003
SOD -Stratospheric ozone depletion	kg R11 eq	EDIP 2003

2.7. Raw material

2.7.1. Epoxy Resin Materials

This study was conducted using more than 85% epoxy resin, bisphenol diglycidyl ether (E-44 and E-51), produced using bisphenol A (DPP) and epichlorohydrin (ECH). The molecule comprises a hydroxyl group, while an epoxy group is present at the end of the chain, enhancing reactivity. Moreover, the DPP structure provides desirable heat characteristics, strength, and toughness. Epoxy resin possesses excellent weather tolerance compared to hydrogenated bisphenol A; it can reduce overall cost and enhance durability. Moreover, its toughness characteristics fulfill the mechanical needs for pavements, specifically considering heat-based surface cracks. In contrast, bisphenol A epoxy resin cracks easily. Furthermore, this resin possesses lesser viscosity, offering superior workability, specifically for low-temperature construction. Table 3 lists the physicochemical characteristics of epoxy resin.

Table 3 Physico-chemical characteristics of epoxy resin.

Type	Viscosity (Mpas)	Density (g/cm3)	Epoxy number (mol/100g)	Molecular weight (g/mol)
Bisphenol A epoxy resin	30.000	1.17	0.49	450

2.7.2. PET Recycled aggregate

In this study, the PET material was obtained from a waste bank in the Yogyakarta area. The physical and mechanical characteristics of PET can be seen in Table 4. PET plastic is segregated based on particle size, as depicted in Figure 1. The PET pellets are 1 mm (small) to 5 mm (large) in size. Initially the PET particles must be cleaned and washed with water to eliminate any surface impurities. After that PET particles were mixed with Epoxy resin and dry at room temperature.

Table 4 Physical properties.

Physical properties of PET	Results
Colour	Clear
Shape of particle	Flat
Specific gravity	1.42
Specific density	~ 1.35 g/cm3
Bulk density	~ 550 kg/m3
Size	1 mm, 3 mm, 5 mm
Tensile strength	59.8 MPa
Viscosity	0.62 to 0.75 dL/g
Approx. melting point	200-250 ºC

2.8. The eco-brick mixture manufacturing process

The purpose of this phase is to determine the environmental impacts resulting from the production of the eco-brick mixes investigated in this study. Energy consumption in the production of eco-brick mixes consists mainly of electricity consumption for the stirring process. The stirring machine consumes electricity to mix the particles of PET and the epoxy resin, while only room air or sun is used for the drying process of the eco-bricks.

3. Results and discussion

3.1 Performance analysis of eco-brick-based PET particles and epoxy resin materials

The eco-brick is the most important material in a building, so the functional unit determined in the study is the weight of 1 kg of eco-brick. The production of eco-bricks starts with the mixing process of PET particles and epoxy resin. The raw materials are stirred with a mixing machine. Then the molding process takes place in the brick mould. After the eco-brick is moulded, it is dried by sunlight or at room temperature. The results of the analysis of the characteristics of eco brick can be seen in Table 5.

Table 5 LCI results.

	Materials	Quantity	Unit	Origin
Input	Polyethylene terephthalate granulate (PET)	0,11	kg	Calculated
	Epoxy resin	0,89	kg	Calculated
	Electricity	62,625	kWh	Calculated
Output	Eco-brick	1	kg	Calculated

From the data collected during the LCI process, an LCA model was created using GaBi software. As shown in Figure 2, this model describes in detail the inputs and outputs involved in brick production. The potential environmental impacts were then analysed using the EDP 2003 method.

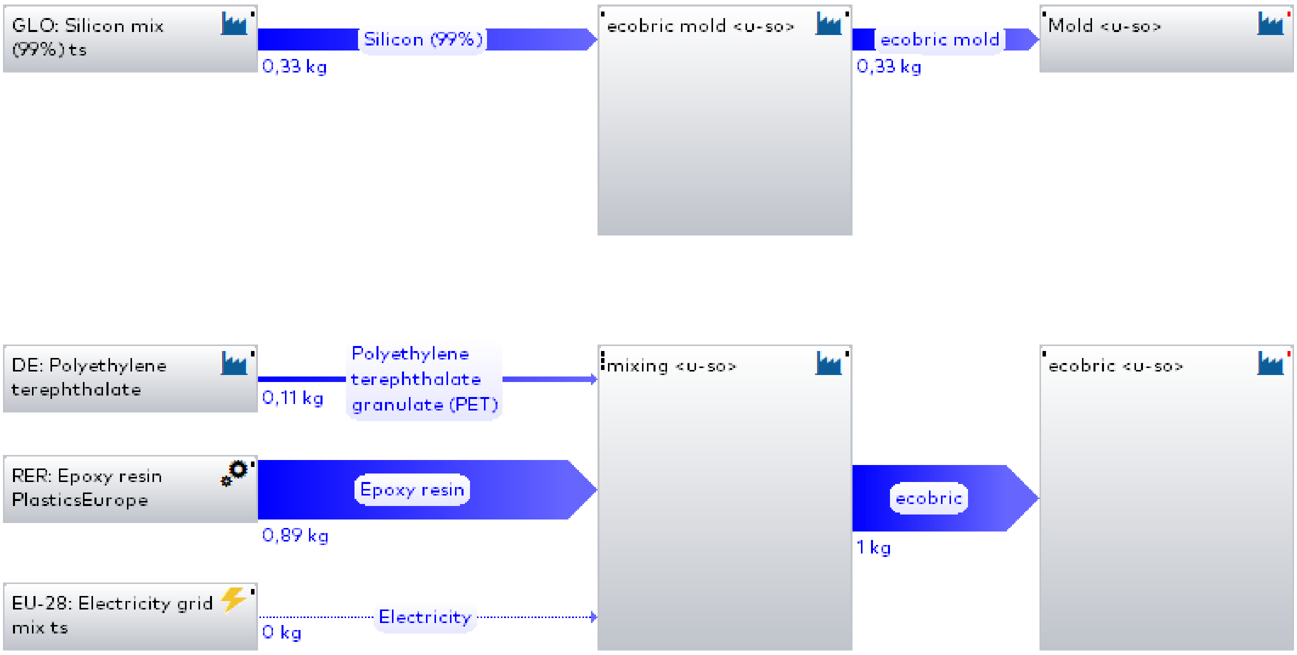

Figure 2 Life Cycle assessment modelling using Gabi.

As shown in Figure 3 there are five categories of environmental impacts derived from the LCIA results. The five categories are GWP, acidification potential, photochemical ozone formation (impacts on human health and materials), ozone formation (impacts on vegetables), and stratospheric ozone layer depletion. This GWP category focuses on the environmental impacts of global warming. The production process of eco-bricks has impacted the GWP for 100 years. The largest impact is electricity consumption, which is 24.7 kg CO2 eq. In addition, the use of epoxy resin produces 7.17 kg CO2 eq. The second category is acidification potential. This category is about the impact of acidification on the environment. The results of the LCIA diagram in the eco-brick production process show that the biggest impact on the eco-brick production process is electricity consumption, with a total of 0.94 m2 UES. The third category is the formation of photochemical ozone. In this LCIA diagram, the eco-brick production process has the largest impact of 5,036 e-3 pers*ppm*hours. Photochemical ozone formation analyses the impact of ozone on human health. The 4th category of ozone formation focuses on the potential for ozone depletion. Based on the LCIA's findings on eco-brick production, the largest impact is found to be electrical energy, contributing

71.32 m2 UES*ppm*hours. The 5th category is stratospheric ozone depletion. In the LCIA results, it is found that the electrical energy is also the largest, contributing 7.394e-13 kg R11 eq. Based on the LCA analysis of the production process of eco-bricks, it can be seen that the consumption of electrical energy has a greater impact on the environment. The recommendation for reducing the environmental impact of eco-brick production is, therefore, to save energy and use natural resources efficiently.

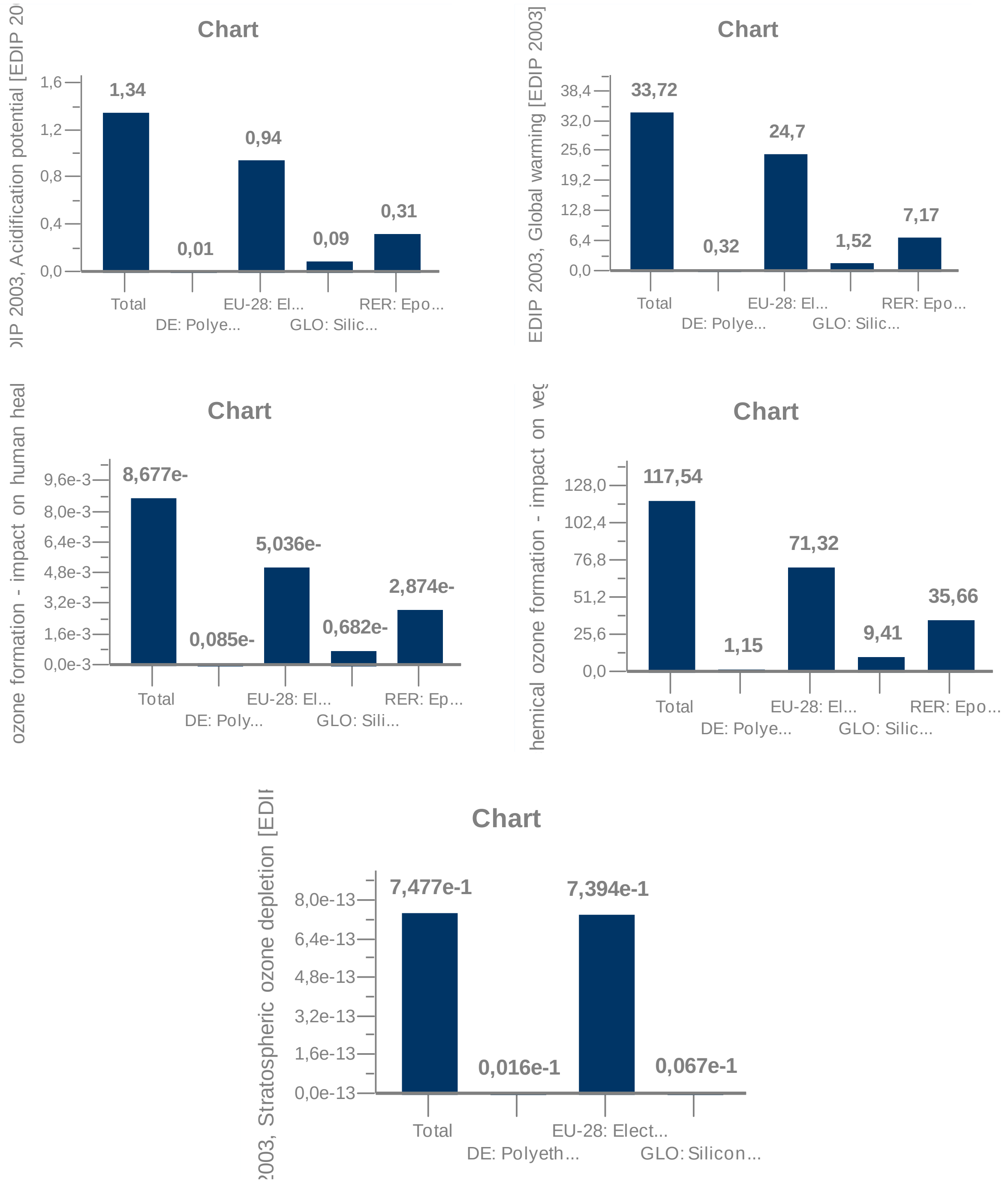

Figure 3 LCIA Diagram.

3.2 Comparative LCA of eco-brick based on epoxy resin-pet, clay-pet, and cement-pet

In this study, eco-bricks were compared with several other scenarios. Eco-bricks were compared with a mixture of clay and PET and a mixture of cement and PET. These are forms of eco-bricks that are commonly found in the community. Some mixtures of eco-bricks can be seen in Table 6.

Table 6 LCI of Clay-PET.

	Materials	Quantity	Unit
Input	Polyethylene terephthalate granulate (PET)	0,5	kg
	Clay	0,5	kg
	Electricity	62,625	kWh
Output	Eco-brick	1	kg

Table 7 LCI of Cement-PET.

	Materials	Quantity	Unit
Input	Polyethylene terephthalate granulate (PET)	0,5	kg
	Cement	0,5	kg
	Electricity	62,625	kWh
Output	Eco-brick	1	kg

In this research, life cycle analysis aims to consider every activity, raw material, and process that may have an impact on the environment contained in the input, output, and waste of a product. In the LCI analysis, eco-bricks and bricks made of clay PET and cement PET are compared. In this study, the adhesive types clay, cement, and epoxy resin were compared. The results of the analysis can be seen in Table 8 with different adhesive units. From the analysis of Table 8, it can be seen that the clay adhesive material has the least potential impact compared to the others. This is because clay is a natural material that is readily available in the environment. Furthermore, clay has a mineralogical composition and good physical, mechanical, and thermal properties (Ramos Huarachi et al 2020). However, the production of bricks from clay has an impact on the environment, as the production of bricks from clay requires non-renewable raw materials. In addition, the production of bricks from clay requires high temperatures for curing, so the energy demand is also high (Galan-Marin et al 2016). This combustion process releases greenhouse gases that lead to global warming (ML et al 2021).

Table 8 Results of the characterization

Impact Category	Impact Results			Unit
	Epoxy resin-PET	Clay-PET	Cement-PET	
Acidification Potential	1,34	1,05	1,08	m2 UES
Global warming	33,72	27,7	28,15	kg CO2 eq
Photochemical ozone formation (impact on human health and materials)	8,68e-3	6,10e-3	6,26 e-3	pers*ppm*hours
ozone formation (impact on the vegetable)	118	85,9	88,26	m2 UES*ppm*hours
Stratospheric ozone depletion	7,48e-13	7,53e-13	7,53e-13	kg R11 eq

The adhesive comparison of eco-brick production can be seen in Figure 4. Based on these results, the biggest impact of eco-brick making is both PET -epoxy resin, PET -clay, and PET -cement on OF (ozone formation) and global warming (GWP). The environmental impact of using epoxy resin is quite high because epoxy resin is a chemical that is mainly petroleum and therefore has a large environmental impact (Lemesle et al 2020). Therefore, it is necessary that epoxy resin materials can be replaced by bio-based epoxy resins. One of the applicable concepts to promote sustainability is the use of cleaner production. Cleaner production is an environmental management strategy used in the production chain to increase the efficient use of raw materials, energy, and water and to minimise waste and emissions generated by the production process (Magnusson et al 2022). An example is the 3Rs strategy, namely reuse, recycle, and recover.

Epoxy resin is a very important polymer or semi-polymer of the thermoplastic family. Epoxy resins play an important role in composite materials. Petroleum-based epoxy monomers have excellent tensile strength, high stiffness, and electrical strength. Epoxy resins are used in various fields, such as construction, automotive, and aerospace. The use of epoxy resins is widespread because they have good mechanical strength, dimensional stability, good wettability, fire resistance, good chemical resistance, and low drying shrinkage (Paluvai et al 2014). In this study, the compressive strength of Clay-Pet, Cement-Pet, and Eco-brick was compared. The results of the compression test comparison can be seen in Table 9.

Eco-brick mixed with epoxy resin and PET has high compressive strength compared to the compressive strength of the other mixes. This is what causes the PET and epoxy resin mixed eco-brick to have a high impact, but the advantage of this is that PET and Epoxy resin-based eco-brick do not need to be burned, so it does not cause pollution. In addition, this pet and epoxy resin mixture eco-brick has the greatest strength compared to the others, so when applied to building construction, it will make the building stronger. However, a more holistic study of plastic waste incorporated in the construction sector is needed, arena this will be able to encourage a food term perspective so that it is possible to conduct complete food term research related to the environmental and health impacts generated from the PET mixture.

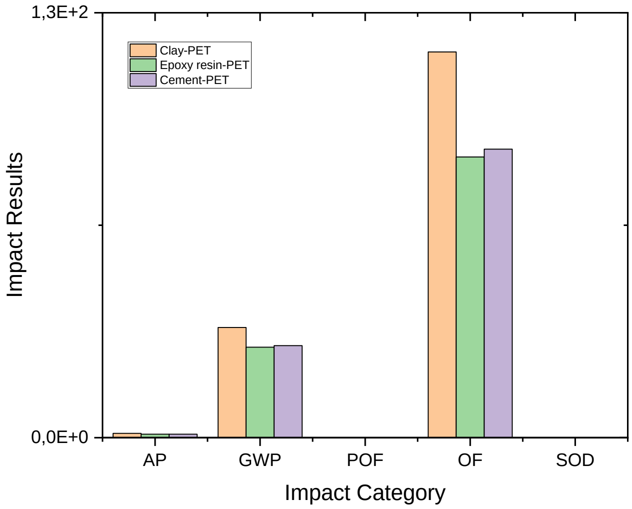

Figure 4 Environmental impact of eco-brick production.

Table 9 Comparison of eco-brick production based on compressive strength.

Author	Year	Mixing	Maximal MPa	Reference
del Rey Castillo, Enrique	2020	PET and Cement	20	(del Rey Castillo et al 2020)
Akinyele, J. O.	2020	PET and Clay	11.02	(Akinyele, Igba, and Adigun 2020)
Taaffe, Jonathan	2014	PET bottle	38	(Taaffe et al 2014)

Based on the results of the statistical analysis of the comparison between the type of adhesive in the manufacture of eco-bricks with the results of the compression test can be seen in **Erro! Fonte de referência não encontrada.**.

Table 10 Statistic analysis results.

Model		Unstandardized B	Coefficients Std Error	Standardized Coefficients Beta	t	Sig
1	(Constant)	2.776	.833		3.334	.008
	Compressive strength	-.010	0.26	-.115	-.366	.722

Analysis of variance (ANOVA) was applied to evaluate the main effects and to analyse the interactions between the input parameters. The factors clay, cement, and epoxy adhesive had a highly significant effect ($p < 0.05$). The significance value of the type of adhesive in eco-bricks on the compressive strength is 0.008 < 0.05. It can be deduced that the use of different adhesives has a significant influence on compressive strength.

Figure 5 shows that by using epoxy resin, a higher compressive strength can be achieved than with other mixtures. The addition of epoxy resin as an adhesive has a great influence on the compressive strength of the eco-briquette. This proves that epoxy resin is a polymer material that has high mechanical strength and good adhesion data (Abbasi et al 2021), so the use of epoxy resin as a mixture can be used in buildings. Epoxy resin is the main thermosetting resin used in high-performance development. Epoxy resin is the first choice for bonding material fragments such as steel, copper, wood, iron, cement, plastic and other composites (Deriszadeh et al 2019).

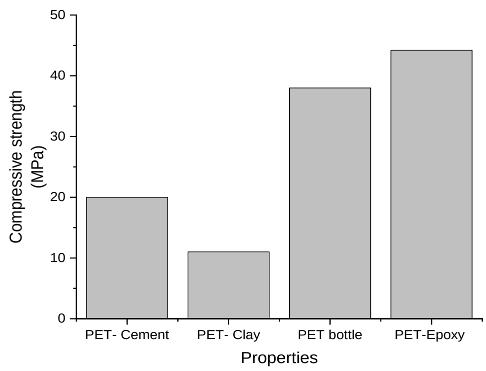

Figure 5 Compressive strength comparison of eco-brick.

4. Conclusions

LCA is a method designed to measure the environmental impact of a product throughout its life cycle. From the literature that has been cited in this study, it can be said that the implementation of LCA provides many alternatives to improve detailed studies on environmental and economic impact assessment. In line with this, it is possible for LCA to verify the reuse of plastic waste in the field of building construction. In this study, an LCA methodology based on ISO 14040/14044 is applied to assess the environmental impacts associated with the use of eco-bricks made from a mixture of epoxy resin and PET. The LCA of these eco-bricks was made with respect to the stages of production or gate-to-gate. LCI inputs are obtained mainly from laboratory tests and some databases. In this research, GaBI is the software used to analyze LCA, and the CML 2001 impact assessment method was used to model and evaluate eco-bricks. Based on the results obtained, this study shows that the mixing stage using electricity is the highest contributor to the impact category. When compared to the process of making eco-bricks, the addition of PET mixture and epoxy resin has a high impact category than others. This is because the epoxy resin is a chemical, so there needs to be a substitution to make bio epoxy resin. For future research, an economic evaluation can be considered on plastic recycling that can measure the savings impact generated by PET incorporation. It is also necessary to measure the environmental impact on the construction sector.

Ethical considerations

Not applicable.

Conflict of Interest

The authors declare that they have no conflict of interest.

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