Terracotta Industry: Dealing with Climate Change through Material Circularity

JSACE 1/37

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Received 2024/01/05

Accepted after revision 2024/11/08

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https://doi.org/10.5755/j01.sace.37.1.35950

Abstract

In Indonesia, the processing of construction raw materials from industrial activity, particularly terracotta, is one of the largest contributors to climate change. This study reviews the terracotta industry in the context of their impact on climate change towards more environmentally friendly processes. The study involved the concept of material circularity as a response to prevent increases in global temperature and reduce atmospheric pollution. Terracotta, a clay-based material in the form of bricks and roof tiles, is the most commonly used building material for housing in Indonesia. Logede Village in Kebumen, Central Java, is a terracotta-producing village that has been active since the Dutch colonial era (1910-1949), and its production continues to grow until now. The purpose of this study is to review the terracotta industry process in the context of their impact on climate change towards more environmentally friendly processes. The analysis was conducted through field observation and interviews, followed by Material Reutilization Score (MRS) calculation and analysis. The result indicated some practices are considered environmentally friendly, as they use recyclable raw materials on-site and consume low electricity. However, the extraction of the raw material and the disposal of waste were not properly managed. This study recommends finding alternative aggregates to replace sand, using fly ash in the terracotta mixture to reduce the clay composition, and involving government and environmental experts to enable widespread waste management.

Keywords: climate change; environmental friendly; material circularity; terracotta industry; village.

Introduction

In recent years, the environmental impact of the construction industry has gained significant attention due to its substantial contribution to global emissions. The buildings and the construction sector contributed up to 39% of energy and process-related carbon dioxide (CO_2) emissions in 2018 (IEA, 2019). In this sector, 11% of the emission was caused by the manufacturing of building construction materials. This data underscores the role of sectors in global emissions, and it is important to explore the limitations of addressing the emissions from a smaller-scale industry. Nowadays, the manufacturing industry is one of the largest contributors to greenhouse gas emissions (United Nations, 2022). For instance, Indonesia was the 6th largest terracotta producer in the world in 2012 (Global Business Guide Indonesia, 2014), making a significant case for understanding the environmental impact of the sector. Terracotta is a commonly used building

Journal of Sustainable Architecture and Civil Engineering
Vol. 1 / No. 37 / 2025
pp. 127-139
DOI 10.5755/j01.sace.37.1.35950

material in Indonesia (Umam & Astuti, 2022). Until Mei 2024, the need for houses in Indonesia will increase in line with the increase in the population growth rate of 1.11% (Badan Pusat Statistik, 2024). This causes the demand for terracotta products as a material for roofs and walls of houses in Indonesia to increase.

The circular economy (CE) concept promoted by Annie Leopard (2011) and Ellen MacArthur (2019) has been proposed as a solution to reduce waste in material processing industries like terracotta. Although these studies highlight the potential for efficiency, further research is needed to critically evaluate the effectiveness of CE in traditional industries with limited technological access, such as terracotta production in Indonesia. In the terracotta industry sector, this concept can be studied from the extraction to production stages (Leonard, 2011). The terracotta industry helps industrial activities use natural resources efficiently and reduces production waste (MacArthur, 2019a).

Apart from reducing economic expenses in industrial processes, this concept also directs industry stakeholders to recycle waste wisely (MacArthur, 2019b). The flow density in the material circularity model can be seen from the value of the Material Reutilization Score (MRS), which calculates how much waste is reused from the first processing of a product (Niero & Kalbar, 2019).

Based on Kemenperin.go.id (2016), the terracotta generally used in homes comes from the three largest terracotta-producing regions in Indonesia, namely North Sumatra, West Java, and Central Java. Logede Village, Kebumen, Central Java, is one of the oldest terracotta producers in Indonesia (Kemdikbud, 2014). The tile and brick industry is one of the main sectors supporting the community's economy, with a significant increase noted until 2022.

The purpose of this study is to review the terracotta industry process in the context of their impact on climate change towards more environmentally friendly processes. This study recommends alternative aggregates to reduce the environmental impact of climate change and to make the terracotta industry processes in Logede Village, Kebumen, more environmentally friendly.

Literature Review

An Impact of Industrial Activities on Climate Change

Climate change can be caused by human activities such as burning fossil fuels, burning forests, transportation activities, activities in factories, etc. (Miller & Spoolman, 2008). These activities produce greenhouse gasses, leading to global warming and climate change. Climate change is a long-term phenomenon that poses global challenges to the environmental, socio-political, and socio-economic sectors (Abbas et al., 2022).

Although factory and transportation activities are often found in urban areas, the impacts of climate change are also common in rural areas (Borras Jr. et al., 2022). A village with natural wealth that should be protected has now been exploited for industrial purposes. Borras Jr. et al. argue that the use of natural resources on a large scale reduces the quality of ecosystems in rural areas. In addition, industrial activities carried out directly in the rural context will cause air pollution and reduce the quality of agriculture, which is in line with the reduced welfare of the villagers.

Material Economy and Circular Economy (CE) in Facing Climate Change

The material economy concept was developed by Annie Leonard in 2011 in a book entitled "Story Of Stuff, Referenced and Annotated Script." The material economy describes a linear process where materials are extracted, produced, distributed, consumed, and disposed of (Leonard, 2011). In the process chain, the actors involved include suppliers, industry, distributors, and buyers (Shambu, 2019). With the limited availability of natural resources, humans have consumed 30% of natural resources and produced 30% of waste (Leonard, 2011). All natural resources obtained from the extraction process have become input for the production process.

A circular economic model can replace the linear process in the material economy through the circular economy (CE) concept (Kirchherr, 2022). This concept was first promoted by the Ellen

MacArthur Foundation in 2019 and is considered a good response to climate change issues. The CE approach has a goal of reducing CO_2 emissions from the industrial sector by 40% or 3.7 billion tonnes by 2050 (MacArthur, 2019b).

According to MacArthur, the CE concept can be applied in the industrial process of an item or the process of using it until the end of its useful life. Reusing products or components and recycling raw materials can create a regenerative process. The CE process attempts to maintain the selling value of each industrial component and does not allow waste to enter the environment (Sikdar, 2019). The final model resulting from the concept of CE has a circular cyclical nature to remove waste from industrial processes and the use of an item (MacArthur, 2019a).

Material Circularity as Solutions for Responding to Climate Change

Material circularity is a principle that was developed based on two ideas, namely the material economy developed by Annie Leonard in 2011 in the book "Story Of Stuff, Referenced and Annotated Script" and the CE principle promoted by the Ellen MacArthur Foundation in 2019. Both concepts aim to reduce waste pollution that is wasted into the atmosphere to reduce the impact of the greenhouse gas effect and climate change.

In material economics, Annie Leonard questions where an object goes after the disposal stage within a linear consumption system (Leonard, 2011). This inquiry was addressed by the concept of the CE developed by Ellen MacArthur, which recommends a circular lifecycle for objects (MacArthur, 2019b). To achieve circularity, Ellen MacArthur proposes the practices of recycling and reusing waste materials. Given that this writing pertains to the field of architecture, the focus is placed on the concept of circular materials and not on the economic aspects of a material.

Issues in Terracotta Industry

Bricks are made of clay, which has plastic properties when mixed with water (Widodo & Artiningsih, 2021). Widodo & Artiningsih (2021) added that a mixture of soil and water is also mixed with salt content and other organic matter in the manufacturing process. Furthermore, the mixture will be burned at 450-750°C to reduce the water content in it so that the water evaporates and the mixture becomes hard (Musa & Kadir, 2021). After that, the product was fired again at 950- 1250°C to remove the CO_2 content (Rahman et al., 2021). Meanwhile, roof tile is molded in the same way as bricks, but the tile is molded more thinly and lightly (Duggal, 2009).

The terracotta industry can be carried out in two ways: by handmade and mechanically (Prieto et al., 2022). The handmade industry is done manually with human power from excavation, mixing materials, and molding. With this, the product density is 40% lower than the mechanical process because human pressure in the handmade process is not as intense as machine power. Generally, the handmade terracotta industry uses a burning system by drying it in the sun (Dabaieh et al., 2020). Drying the product in the sun with the condition that the product has a low density allows air to flow through the pores of the terracotta so that the product is not easily moldy. Dabaieh et al. argue that drying in the sun is considered energy efficient, produces low toxicity, and does not produce polluting waste for the environment. Meanwhile, burning with fire will produce pollutants released into the atmosphere and increase the amount of CO_2 in the air, resulting in global warming (Huovila et al., 2019).

In practice, the terracotta industrial process can harm the environment. The extraction process in terracotta industrial activities can reduce the raw materials available in nature, such as clay, sand, and firewood (Bhoopathy & Subramanian, 2022; UNEP, 2019; Biswas et al., 2018; Azevedo et al., 2020; Schmid et al., 2020).

In addition to reducing sand as a raw material for terracotta, the habitat of living things around the sea will also be lost due to sand extraction activities (Bhoopathy & Subramanian, 2022). To face the sand crisis, the material construction industry should raise awareness and seek alternative raw materials such as aggregates (UNEP, 2019). According to several journals, an alternative to sand can be glass waste, which is crushed first and recycled into aggregate (Costa et al., 2009) In addition, sawdust also has the potential to be an aggregate for brick (Shafiquzzaman et al., 2022). Currently, granite and eggshells are also being developed as terracotta aggregates (Ngayakamo et al., 2020).

The terracotta burning process has the potential to higher the ambient temperature (Saha et al., 2021). This process also produces harmful emissions (Kulatunga et al., 2020). The gas from burning also produces greenhouse gasses in the atmosphere, which causes air pollution. Specifically, each final terracotta product produces 0.5 kg CO_2 per product (Schmid et al., 2020). However, efforts can be made to reuse industrial waste for input in the following production process. These efforts can reduce 56% - 64% of CO_2 during the industrial process. Thus, the process of the terracotta industry can be assessed for its circularity using the concept of circular material as a response to climate change. The concept of material economy and CE respond to climate change, resulting from waste accumulation and pollution.

Fig. 1

Hydraulic Machine for Molding Tiles

Moreover, The terracotta industry in Logede Village, Kebumen, located in Indonesia, has operated since 1910. At that time, the tile molding process was still manual, using human labor, and the mixture of roof tiles and bricks still used pure clay without any aggregate. In the early 2000s, the clay was mixed with sand for roof tiles and bran for bricks. This happens because the texture of the clay is getting softer, and it needs to be mixed with aggregate to make it easy to mold. Around 2017, hydraulic machines began to appear among the roof tile industry players in Logede Village. Hydraulic Machine is a machine with electric power to assist in molding roof tiles (Fig.1). Although the use of hydraulic machines in the terracotta industrial process speeds up the duration of work for industrial players, the use of these machines results in increased use of electricity and consumption of fossil fuels which hurt the environment. This study discusses the industrial process of terracotta material produced in Logede Village, Kebumen. The study involves a circular material concept as a response to the issue of climate change, which causes an increase in CO_2 and ambient temperature.

Material and Methods

Case Study Location: Logede Village, Kebumen, Central Java

Logede Village has an area of 116 hectares in the Pejagoan sub-district, which is one of 3 roof tile and brick-producing sub-districts in the Sokka region, Kebumen Regency. This village has 57 Ha of settlements and 59 Ha of rice fields. In the Dutch colonial era (around 1910), the Dutch began to produce bricks and roof tiles in the Sokka area to build stations and houses in the village.

The main industry in Logede Village is roof tiles, while bricks are a secondary industry needed at the tile-burning stage. However, the bricks produced directly in Logede Village are also used as construction materials for houses in Logede Village, and their distribution has spread to Central Java. The distribution of roof tiles produced in Logede Village has a larger reach because they have been sent overseas.

Terracotta Industrial Process in Logede Village

The process of the brick and tile industry starts from extraction, mixing or milling, molding, drying, and burning. However, there are some differences in the blending process, production duration, and production location (e.g. Fig.2). For the brick industry, clay is taken from the fields. Next, mix the clay with dry rice bran in a ratio of 4:1 with sufficient water until the soil reaches a plastic texture. The mixing of raw materials is still done manually using a gejik, which is a wire that is attached to a bent iron pole and functions to smooth the clay. Next, molding is done using a wooden board. After that, the bricks were dried in the sun for two days. The whole series of processes takes place in the rice fields. For the burning process, the results of molding the sun-dried bricks are brought by truck to the topbong or kiln located 1-2 km from the rice fields. Then, the bricks are burned together with the tiles that are ready to be burned.

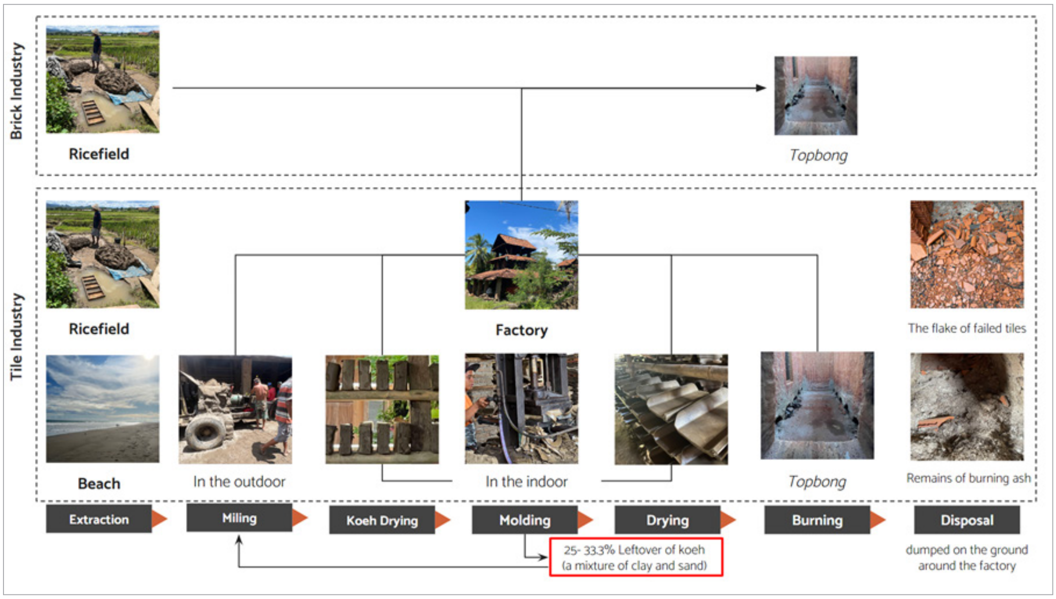


Fig. 2

Terracotta Industrial Process and Material Locations

Meanwhile, in the roof tile industry, the entire series of processes, from mixing, molding, drying, and burning, are carried out in one place. Initially, raw clay materials were brought from the fields to the factory using trucks with a distance of 1-2 km, and beach sand raw materials were brought from the beach, which was 11 km away, using trucks. Next, a grinding process is carried out with a machine to mix clay and sand with a ratio of 6:1. The milling process will produce a solid block called "*koeh*". There are 3 types of roof tiles produced in Logede Village, Kebumen, namely *marando*, *plentong*, and *magas* (e.g. Fig.3).

The three types of roof tile have different weights. Therefore, the *koeh* weight used for each type of tile is also different. For making one piece of *marando* type, 4 kg of *koeh* is needed, *plentong* requires 3 kg of *koeh* per piece, and *magas* requires 3.5 kg of *koeh* per piece. After the *koeh* is produced from the mixing process, it is first dried in the sun for 10 days to reduce the water content in the mixture. After that, the *koeh* is molded according to the type of roof tile. After molding, the weight of each type of tile is reduced. For *marando*, the weight is 3 kg, *plentong* is 2 kg, and *magas* is 2.5 kg. So, after the drying and molding process, the weight of the tile mixture is reduced by around one kilogram. After the tile is molded, it is dried for 3 days

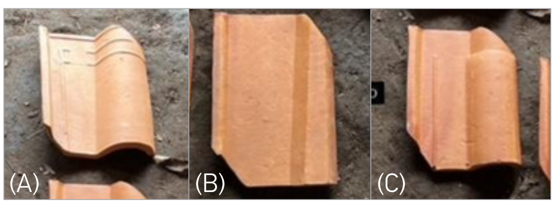


Fig. 3

The Three Types of Roof Tile in Logede Village:
(A) Marando,
(B) Plentong,
(C) Magas
(Source: Personal Documentation)

if it is in the dry season and 1 week during the rainy season. Next, combustion is carried out in the topbong. There are 2 types of topbong, one with a capacity of 18,000 tiles and another capacity of 25,000 tiles.

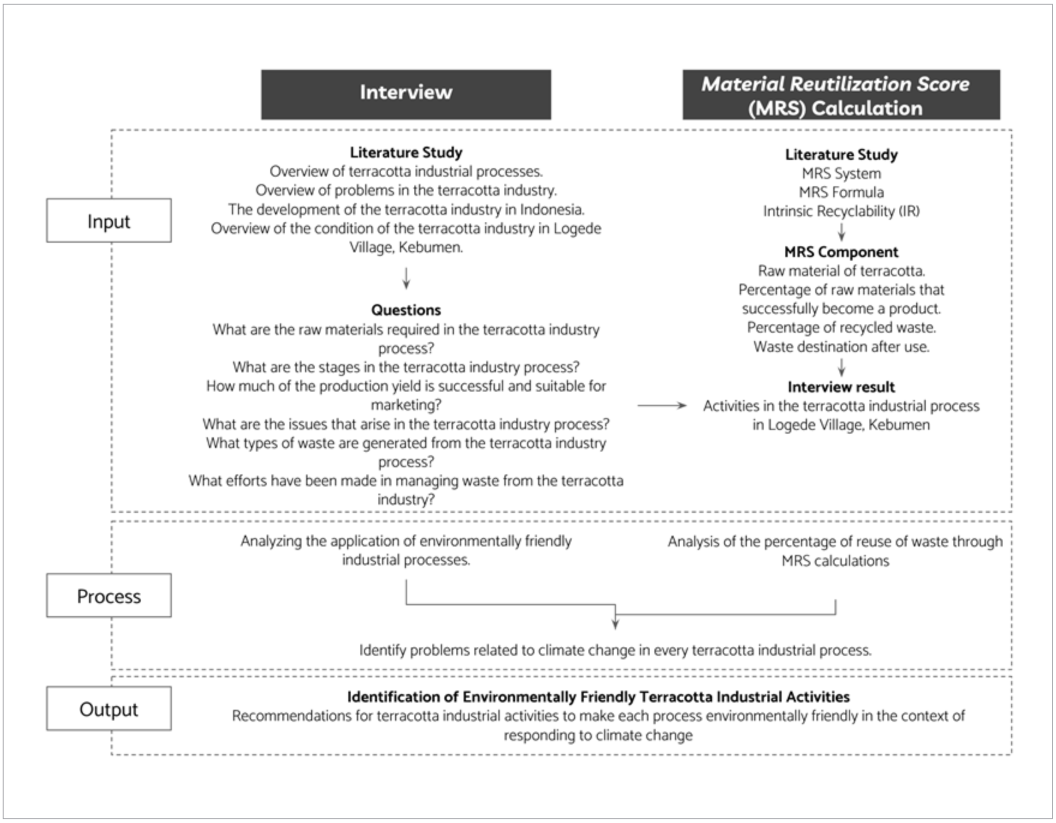
The roof tiles are fired together with the bricks in the topbong. Burning in the topbong requires 3 firewood trucks to burn in the topbong with a capacity of 18,000. Firewood is obtained from Wonosobo, which is 71 km from Kebumen, and West Java which is 300 km from Kebumen. The burning process begins with a small fire that burns for 4 hours. Next, the firewood produces a big fire, and after 3 days, the process of burning the tiles and bricks is complete.

Research Framework

Methods in achieving the purpose of writing include interviews and MRS calculations. The flow of the study framework can be seen in the Fig.4.

Fig. 4

Study Framework



Interviews and MRS calculations will be used to identify environmental issues in the Logede Village terracotta industry and recommend solutions. The output is in the form of recommendations regarding the environmentally friendly terracotta industry in dealing with climate change issues.

Interview with Terracotta Craftsmen in Logede Village, Kebumen

This study uses a field study method in the form of interviews with workers in a terracotta factory in Logede Village, Kebumen. The field study was conducted for two consecutive days on April 2023 in five terracotta factories (Table 1). Interviews were conducted with two workers per factory.

In Logede village, there are around 100 terracotta home factories. The scope of this interview includes raw materials, terracotta industrial processes, and the amount of waste from industrial processes. This information is extracted to serve as input for MRS calculations and problem analysis in the terracotta industrial process in Logede Village, Kebumen.

Industry	Factory	Founding Year	Product Capacity/ Production Phase (about 2 weeks)	Industry Process (Manually/ Mechanically)
Roof Tiles	A	1920	18000 pieces	Mechanically
	B	1970	5000 pieces	Mix
	C	1995	5000 pieces	Mix
Bricks	D	1980	1000 pieces	Manually
	E	1990	1000 pieces	Manually

Table 1

Specifications of the Terracotta Factory Visited

Material Circularity Flow using Material Reutilization Score (MRS)

Material Reutilization Score (MRS) to calculate circularity based on how much recycling has been carried out by the terracotta industry in Logede Village, Kebumen (**Eq. 1**). This methodology has the intention to increase the material reutilization potential of a product (De Pascale et al., 2021). The calculation of MRS considers the technical cycle of a product (Lindgreen et al., 2021). MRS has a final value ranging from 0 to 100% (Cradle to Cradle Products Innovation Institute, 2016). The MRS standard requirement level: 1) Bronze - the product has an MRS of 35%; 2) Silver - the product has an MRS of 50%; 3) Gold - the product has an MRS of 65%; 4) Platinum - the product has an MRS of 100%.

$$\text{MRS}=\frac{[(\%\,IR\ of\ the\ product)*2]+[(\%\,RC\ in\ the\ product)*1]}{3}\times 100 \quad (1)$$

(Niero & Kalbar, 2019)

MRS calculates the recyclability potential of a product considering two variables: the intrinsic recyclability (IR) of the product, which is the percentage of the product that can be recycled at least once after its initial use stage, and the percentage of recycled content (RC) (Niero & Kalbar, 2019). IR can also be defined as a product's recyclability, biodegradability, or compostability (Cradle to Cradle Products Innovation Institute, 2016). Meanwhile, RC refers to a recycled or rapidly renewable product content.

Result & Discussion

Interview Result with Terracotta Craftsmen

From the interview, the study found that after the koeh molding process, the mass of the clay and sand mixture on the tile is reduced by around 25% -33.3% of the initial *koeh* mass (Table 2.). Because the mixture has not gone through the combustion process, it can be ground back into *koeh* for the next tile-making process. The remaining *koeh* is usually reused by terracotta craftsmen for the next roof tile-making process.

Table 2

Koeh Reduction From Process to Make One Clay Roof Tile

Type of Roof Tiles	Raw Materials	Koeh needs at each stage (kg)							*Koeh* reduction after molding process (%)
		Extraction	Miling	*Koeh* Drying	Molding	Drying	Burning	Result	
Marando	Clay	3.42	3.42	4	4	3	3	2.5	25
	Sand	0.57	0.57						
Plentong	Clay	2.57	2.57	3	3	2	2	1.5	33.33
	Sand	0.43	0.43						
Magas	Clay	3	3	3.5	3.5	2.5	2.5	2	28.57
	Sand	0.5	0.5						

The remnants of the failed tiles and ash waste from burning are often found around the factory. In addition, after the tiles have been fired, usually in *topbong* with a capacity of 18,000 roof tiles, there is often a failure in producing 100-1500 tiles. The failed and destroyed roof tiles were irregularly dumped on the ground at the factory terrace and mixed with other wastes. Most of the waste cannot be recycled, which causes industrial waste disposal problems (Gol et al., 2023).

The combustion process itself produces waste in the form of ash from burning firewood, which has not been carried out by waste management. The ashes from the burning are also directly dumped on the ground at the factory terrace. In a more serious manner, ash disposal adversely affects substantial risk to health and the environment (Coutinho et al., 2022; Etchie et al., 2020).

Terracotta industrial activities have a series of processes that have begun to be directed towards environmentally friendly principles, although several stages still have the potential to be made more environmentally friendly through increased circularity (Dabaieh et al., 2020). Special attention is needed to make the terracotta industrial process more environmentally friendly. This is done so that architectural products such as houses and other types of buildings can still use bricks and roof tiles.

The process of making bricks from extraction to drying and the process of making tiles from milling to burning are carried out on-site, thereby reducing transportation energy. In addition, all processes are conducted on-site and practiced traditionally without the help of machines. (Suryantini et al., 2021). This also applies to the process of making roof tiles. Based on the interview, in the process of making roof tiles, the raw material for the clay mixture obtained from molding has been reused, and the rest is reprocessed into koeh for the next roof tile-making process.

On the other hand, the terracotta industrial process produces several negative impacts on the environment. The clay extraction process changes the soil contour and impacts cultivating or gardening activities (Anwar et al., 2019). Sand extraction on the beach causes seawater to rise, increasing the potential for flooding; based on interviews with terracotta industry players in Logede Village, Kebumen, they often move beach locations if the sand on a beach starts to decrease and starts to run out. Terracotta burning activities require firewood, and if forests are continuously cut down for firewood extraction, then the earth will lack sources of clean air, and many creatures will lose their habitat (Huovila et al., 2019). Following the burning process, the roof tile manufacturing procedure will generate the remaining roof tiles that were not successfully produced. According to interview results, for *topbong* with a capacity of 18,000 roof tiles, there is generally a failure in roof tile production with a total of 100-1500 roof tiles. Roof tiles that fail to produce and break are thrown onto the ground, becoming waste that can contaminate the soil.

Result of MRS in the Terracotta Industrial Process in Logede Village, Kebumen

The MRS calculation process requires Intrinsic Recyclability (IR) and Recycle Content (RC). IR refers to the amount of recyclable, compostable, or biodegradable materials contained in a product, whereas RC refers to the amount of recycled material that is contained in a product (Cradle to Cradle Products Innovation Institute, 2016). Transportation from the rice field to the factory covers a distance of two kilometers, while from the beach to the factory covers a distance of 11 kilometers. The average fuel consumption is 58 L/100 km (Tejada et al., 2022). Meanwhile, 1000 liters are equivalent to one cubic meter. To convert the figures to kilograms, the theory that diesel has a density of 830-930 kg/m^3 can be applied (Sarikoc, 2020). Therefore, transportation from the rice field to the factory consumes 0.96 kg of diesel, and transportation from the beach to the factory consumes 15.7 kg of diesel.

From the percentage table of IR and RC, it is found that recycled materials are not used in the entire process of the clay tile and brick industry (Table 3.). On the other hand, recyclable materials have been utilized. In the brick industry process, all stages are carried out in the same location, namely in the field. Therefore, diesel transportation from the rice field to the factory is not required.

Table 3

Percentage of IR and RC in the (A) Clay Roof Tile Industry Process and (B) Clay Brick Industry Process to Fulfill the *Topbong* (9000 Roof Tiles and 9000 Bricks)

(A)

Raw Material		IR	RC
Component	Mass (kg)	Yes/no	Yes/no
Clay	30780	Yes[1]	No
Natural Sand	5130	No[2]	No
Firewood	2400	Yes[3]	No
Diesel for transportation from ricefield to factory	0.96	Yes[4]	No
Diesel for transportation from beach to factory	15.7	Yes[4]	No
Total	38326.66		
Percentage (%)		86.6%	0%

[1] Samsudin et al., 2016; [2] Dassanayaka et al., 2020; [3] Gunatilake, 2021; [4] Pasqualino & Salvado, 2006

(B)

Raw Material		IR	RC
Component	Mass (kg)	Yes/no	Yes/no
Clay	21600	Yes[1]	No
Rice Bran	5400.00	Yes[2]	No
Firewood	2400	Yes[3]	No
Diesel for transportation from ricefield to factory	0.96	Yes[4]	No
Total	29400.96		
Percentage (%)		100%	0%

[1] Samsudin et al., 2016; [2] Singh et al., 2023; [3] Gunatilake, 2021; [4] Pasqualino & Salvado, 2006

$$\text{MRS of Roof Tile} = \frac{[(0.86)*2] + [(0)*1]}{3} \times 100 = 57.33$$

$$\text{MRS of Brick} = \frac{[(1)*2] + [(0)*1]}{3} \times 100 = 66.66$$

Due to the non-utilization of recycled materials in the terracotta manufacturing process in Logede Village, the MRS (Material Recycle Score) for roof tiles is 57.33, while for bricks, it is higher at 66.66. The higher MRS for bricks is attributed to the use of biodegradable aggregates. This value can result in higher scores if waste recycling is implemented throughout the process. Based on the results of the MRS calculation, the terracotta industrial process got a score of 57.33-66.66 because of the use of recyclable materials. If these scores were to be certified in the Cradle to Cradle Products Innovation Institute, each product could receive a rank of Silver and Gold.

Using recyclable and recycled materials can promote the implementation of CE (Oliveira et al., 2022). The MRS score does not achieve 100 because it does not use recycled materials in the process. However, the terracotta industry in Desa Logede has an attempt to achieve an environmentally friendly process. This can be seen from using a mixture of clay and sand (*koeh*) to be reused to continue the next roof tile process, followed by bran and clay reuse in the process of making bricks. However, the entire terracotta industrial process that occurs in Logede Village, Kebumen, has the potential to increase its circularity with recommendations to industry stakeholders in the form of management of waste ash from burning firewood and tile fragments that fail to produce, which are thrown onto the ground.

With this, industry stakeholders must think about alternatives to raw materials as early as possible so that actors in the construction sector can still obtain terracotta material, which is the most widely used material in Indonesia. As alternatives to recycled terracotta aggregates, waste glass powder, granite, eggshell, and sawdust can be recommended (Costa et al., 2019; Ngayakamo et al., 2020; Shafiquzzaman et al., 2022). If the terracotta industrial process in Logede Village, Kebumen has managed waste properly and considered alternative recycled raw materials, then there is a possibility that the circularity value of each material processing will increase, which currently has an existing value of 57.33- 66.66, which can become 100. The environmentally friendly terracotta industrial process will create reciprocity for the industrial, architectural, and environmental fields. The availability of terracotta raw materials in nature makes the field of architecture not lose one of the materials that are widely used, especially in Indonesia.

While no research has quantified the correlation between MRS and environmental impact, theoretically, a higher MRS also relates with reductions in CO2 emissions. A higher RC score suggests that the product incorporated recycled materials, indicating that the production process minimizes raw material extraction, thereby decreasing negative environmental impacts. Additionally, a higher IR score suggests that the product can be recycled after its initial use (Niero & Kalbar, 2019), indicating efforts to enhance material circularity through encouraging the reuse or recycling of product contents.

Based on the literature study, the problem arises that the terracotta burning process can potentially increase the ambient temperature (Saha et al., 2021). In addition, the extraction of firewood causes an ecosystem imbalance, and the extraction of clay can damage the character of the land (Purba et al., 2021). After analyzing the problems from the results of interviews and MRS calculations, some of the problems that arise are in accordance with those discussed in the literature study. However, there are some additional problems, including burning ash and tile chip waste that is directly dumped on the ground and the uncontrolled extraction of raw materials.

Conclusions and Recommendations

This study assesses the environmental impact of the terracotta industry in Logede Village, Kebumen, focusing on mitigating climate change effects. Currently, the industry's circularity values range from 57.33 to 66.66, indicating room for improvement, particularly in utilizing recycled materials throughout production. The firing process generates wood ash waste, and discarded tile fragments contribute to environmental pollution. Additionally, the extraction of beach sand raises concerns about habitat loss and reduced sand availability. Alternative recycled aggregates, such as glass and wood waste and artificial sand, are proposed to address these issues. Recommendations include using fly ash in the mixture to reduce clay composition, reforestation for wood fuel extraction, and the utilization of compost fertilizers from recycled roof tile fragments.

Collaboration among terracotta industry stakeholders and other material sectors, supported by government and environmental experts, is essential for effective waste management and sustainable practices. The government's role would include regulating the environment and policies to promote the usage of recycled materials. Wheres, environmental experts would contribute by advising on the best practices in material use and resource conservation. The implementation of these results might come with potential challenges. For instance, the use of alternative aggregates like fly ash faces barriers, such as the limited availability of high-quality ones in certain regions. This study suggests a supply chain for fly ash and other related materials to overcome this limitation. By enhancing the industry's environmental friendliness, the architectural field can access building materials while minimizing the negative impacts associated with construction activities.

The MRS calculation conducted in this study was able to assess the circularity of the terracotta products, but is unable to quantify its environmental impact values. To further support material circularity, using a Life Cycle Assessment (LCA) for future research is suggested to provide a comprehensive environmental impact evaluation of terracotta products, including the emission caused by the production process. Adopting a Life Cycle Cost Assessment (LCCA) to evaluate the economic costs could also benefit the research and encourage more sustainable practices in architectural products.

Acknowledgment

The authors would like to acknowledge Prof. Nasruddin, Prof. Dr. Payam Shafigh and Dr. Loh for pre-reviewing this study. The authors would also like to thank Kwarista Dharma Smitha, Nisrina Dewi Salsabila, and Kartika Rahmasari from Universitas Indonesia for contributing to and giving feedback on this study.

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