Assessing Local Production, Quality Challenges, and Circular Economy Opportunities for Sustainable Reuse of Clay Roof Tiles in Indonesia

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Abstract. Clay roof tiles remain extensively used in buildings throughout Indonesia, with a substantial portion produced informally in local production centers in Central Java, including in Desa Logede. However, issues arise as these locally produced roof tiles often deviate from established standards in terms of size, durability, and comprehensive quality. As a result, many tiles are left unused and become waste materials, raising environmental concerns due to their accumulation and lack of proper disposal or reuse strategies. Hence, this study serves as a preliminary exploration into the potential repurposing of lower-quality clay roof tiles for alternative applications, aiming to contribute to waste reduction and sustainable material use. The study evaluates existing sustainable practices through field observations and open-ended interviews conducted at the Desa Logede local production center. While Desa Logede demonstrates several localized sustainability initiatives, their scale and impact remain limited. A thorough evaluation of these practices is necessary to understand their effectiveness and degree of alignment with the principles of the circular economy. The literature review confirms that lower-quality clay roof tiles possess repurposing potential, particularly when framed within the circular economy's technical and biological cycles. However, several obstacles persist, including the need for scientific validation, rigorous sustainability assessments, and context-specific strategies to bridge the gap between local practices and global sustainability standards.

Keywords: Clay, Local Product, Circular Economy, Sustainable, Reuse.

1 Introduction

Ever since the pandemic, there has been a global increase in manufacturing industry [1]. Since 2020, the Indonesian government has invested 412 billion USD in developing transportation, industrial, energy, and housing infrastructure projects [2]. One of the industries also affected by these investments is the ceramics industry. Clay tiles are one of the byproducts of the Indonesian ceramic industry, primarily used as roofing materials. Clay roof tiles are building elements used for roofing, made from clay with or

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without the addition of other materials, and fired at a sufficiently high temperature [3]. This building material has advantages such as durability, long-lasting properties, and resistance to fire and pests [4]. Clay roof tiles have been used in Indonesia since ancient times. It is believed that their usage in buildings dates to the Majapahit era in the 15th century. Today, clay roof tiles continue to be extensively used in residential buildings across Indonesia, catering to a wide range of socio-economic groups, from the middle class to the lower-middle class. The production centers are not limited to large-scale industrial facilities but also include local operations managed at a household level. The local production centres still exist and are widespread in Indonesia, especially in Java, because their products are much more affordable compared to those produced on a large-scale industrial level. Nevertheless, 30% of ceramic industry products become waste [5-6].

The problem is that the roof tiles produced at the local production centers often tend to be manufactured without following the standard. According to the Indonesian National Standard (SNI), the characteristics of low-quality clay roof tiles can be determined as follows: (1) uneven surface/cracks/black and brown spots on the surface, (2) water absorption exceeding 12%, (3) flexural load less than 140 N, (4) deviation exceeding 3% from the specified size [3]. Globally, low-quality ceramic industry products are noted to contribute to waste, accounting for a total of 30% of the overall ceramic industry production [4]. Therefore, to support the sustainability of the environment, we will need to lessen the burden it gives to the environment by starting to reuse the lower-quality clay roof.

There are several ways to effectively reuse materials that have become waste, one of which is through the concept of a circular economy. Circular economy is a concept aimed at keeping materials, products, and services in circulation for as long as possible [10]. The concept involves reducing material usage, redesigning materials, products, and services, and minimizing resource consumption by using waste as the primary raw material for producing new materials and products. In relation to lower quality clay roof tiles, Numerous previous studies have explored the use of lower-quality clay roof tiles as a material source for different cycles by implementing the circular economy concept. This concept is unfamiliar in several vernacular buildings in Indonesia, as some have implemented the reuse of waste materials in buildings or other cycles [7]. However, as of now, no similar studies have been conducted in Indonesia.

Therefore, this study is planned as a preliminary investigation to assess the potential conversion of low-quality clay roof tiles for use in other life cycles. Several data collection methods were employed in this study to achieve this. First, the process of making clay roof tiles was observed at one of the local production centers in the village of Logede, Central Java, Indonesia. Open-ended question interviews with clay roof tile craftsmen were also conducted, specifically to supplement data regarding the quality determination process of the fired clay roof tiles and their reuse process. The paper then

proceeds with a literature review of previous research discussing the reuse of clay roof tiles and concludes with an analysis, plans for further study, and conclusions.

2 Literature Review

Case studies based on available literatures and researches may serve as a foundation for further investigation, especially one related to the circular economy. According to Environmental Protection Agency, there are two cycles in the circular economy : the technical cycle and the biological cycle [8]. In the technical cycle, materials go through reuse, repair, and recycling processes. While in the biological cycle, materials are returned to the soil as nutrients.

2.1 Biological Cycle

Quarry Filling and Substrate Culture. Several previous studies explore the possibility of reusing clay roof tiles using the biological cycle method, two of them being mine covers and substrate culture [6]. Quarry filling is an economic activity of a company as it provides employment opportunities in the future and aims to restore vegetation to its surrounding ecosystem consistently [10]. The process helps protect groundwater, reduces ecological footprint, creates new job opportunities, and supports the well-being of the surrounding population. Another option is using it as a substrate culture as a planting medium for growing vegetables and ornamental plants [11-12]. It has high porosity, high water-absorption, non-biodegradability, and light weight. However, when a clay-roof tile is in contact with groundwater, it may become toxic, therefore obtaining approval from the authorities is required when intending to modify the structure of soil sediments [13].

2.2 Technical Cycle

Aggregate for Concrete. One of the potential reuse options for unused ceramic waste, such as clay roof tiles, is as an aggregate for concrete [14]. According to SNI, aggregates include coarse types with particle sizes over 4.75 mm and lightweight types with lower density than normal aggregates [15-16]. Examples of reusing lower-quality clay roof tiles as aggregates for concrete include recycled concrete, roller-compacted concrete pavement (RCCP) and recycled lightweight aggregate concrete (RLAC). When repurposing it as recycled concrete, ceramic waste must undergo a deglazing process before use [17]. However, a few case studies reveal that the strength of concrete exhibits high variability depending on the original ceramic material [18]. One application of recycled concrete using clay roof tile waste is as a roller-compacted concrete pavement (RCCP). The maximum strength of concrete incorporating ceramic waste is achieved when using only 0.5% to 30% of the aggregate [17]. These studies align with previous RCCP research, suggesting that utilizing more than 25% clay-roof tiles waste as an aggregate may reduce the pavement's compressive strength. Furthermore, ceramic waste can be employed in recycled lightweight aggregate concrete (RLAC), which utilizes lightweight aggregates with lower density than normal aggregates [19]. When clay

roof tile waste is used as RLAC aggregates, it enhances compressive strength, splitting tensile strength, and elasticity.

Aggregate for Surface Construction. Unused clay-roof tiles can serve as a valuable component in non-concrete surface construction such as pavements, clay-courts, and water-bound macadam (WBM). Previous studies indicate that the optimal percentage of clay roof tiles as a pavement substance in pavement construction should be within the range of 60%-70% [20-21]. Utilizing clay-roof tiles as a pavement substance enhances the compressive strength, reduces the deformation rate, minimizes granule loss, and promotes a more energy-efficient production process. Apart from pavements, clay-roof tiles find utility in the construction of clay courts. When used in clay courts, they contribute to reducing the pulling force on the legs by decreasing force exertion during movement [22]. Additionally, the construction cost is relatively lower compared to other types of tennis courts [23]. Another application is the conversion of ceramic waste into Water-Bound Macadam (WBM). As WBM, it exhibits an average rutting depth (below 10 mm) [24]. However, effective road cleaning before the slushing process is crucial to prevent the formation of potholes. Achieving a smooth surface may pose challenges and may require an additional asphalt layer.

Porcelain Tiles. Porcelain tiles are tiles made from clay, quartz, and feldspar, which are heated to achieve a glassy and crystalline structure [25]. However, porcelain tiles can be manufactured by incorporating fragments of clay roof tiles into the base material. This not only serves as a means of saving production costs but also aligns with environmental sustainability practices [26-27]. A previous study conducted by El-Fadaly found that the firing process during tile production is faster when using quartz, especially when compared to producing porcelain tiles without clay roof tile fragments [26].

Building Facade. Roof tiles can also be reused as building walls, both in the exterior and interior, according to Escaleira et al. [28]. The walls can be installed in a closed or open manner. In addition, roof tiles can also be reused as a brise soleil. Brise soleil is a part of the building consisting of large inclined slats [5]. This brise soleil is placed at a specified distance from the building facade and is used to reduce heat inside the building by reflecting sunlight [29-30].

3 Case Study : Clay Roof Tile Production in Desa Logede

Desa Logede is a village located in the Kebumen Regency, Central Java Province, Indonesia. It is one of several villages in the Kebumen Regency that serves as a center for Sokka-type roof tile production. The village has been involved in clay-roof tiles manufacturing since the 1990s. In 2023, The recorded number of topbong, or kilns for clay roof tile firing production, reached eight. Houses in Desa Logede typically have one to two floors. However, for the topbong owners, their houses are usually situated adjacent to the kilns, facilitating easy access to the firing area for the owners.

Clay is the primary material used for clay roof tiles in Desa Logede and is typically obtained from excavations approximately 130 cm below the surface. According to a local resident of Logede, the areas where clay is extracted are converted into rice fields for 15 years before the clay excavation process is repeated. Hence, a mutual relationship between clay roof tile craftsmen and farmers can be observed. However, there is currently a decline in clay quality, leading roof tile craftsmen to add sand as an additive. The detailed stages of clay roof tile production are as follows:

Extraction. The primary materials used in roof tile production are clay, water, sand, and firewood as fuel for the kilns. The clay is sourced from Desa Logede itself, with a distance of approximately 1-2 km (from the fields to the kilns). Sand extraction is carried out at Petanahan Beach, which is around 11 km away. Firewood is obtained from the city of Wonosobo, located about 71 km away, or from the West Java province, which is approximately 300 km away.

Milling & Drying. The milling process is conducted using a mobile mill in Desa Logede powered by diesel fuel and is performed at least several times. Each milling process creates 15,000 "koeh" or clay dough, cut manually into block shapes. After milling, the clay doughs are dried for ten days in a covered area away from direct sunlight.

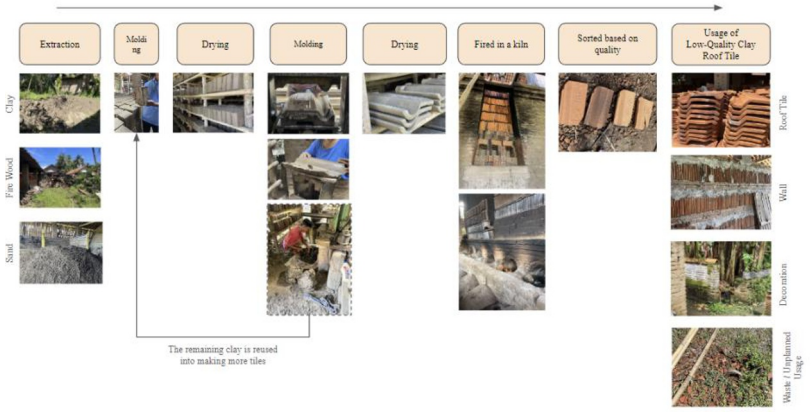
Molding, Glazing, and Drying. Following the drying process, the clay doughs are molded using either manual or hydraulic press machines. After molding, the final roof-tile shapes are coated with diesel fuel as glazing and then dried in the sunlight for 6 hours.

Firing. The firing process takes place in kilns using firewood as the fuel. The clays then stacked in the kilns are arranged from bottom to top, combining not only roof tiles but also clay bricks. In the first 6 hours, a small fire is lit. In the following two days, the fire is intensified using a blower to blow the firewood flames into the kilns.

Screening & Storage. The first post-firing step is quality checking through a screening process. After screening, the roof tiles and bricks are stored by stacking to facilitate the cooling process after firing. Screening is the final process for craftsmen to determine the quality of clay roof tiles. According to the interview results, the quality of roof tiles can be divided into four categories: KW1, KW2, KW3, and KW4. KW1 represents the best quality roof tiles characterized by a perfect red color. On the contrary, KW4 is the lowest quality with indications of cracks on the surface and a pale-yellow color, or still not having undergone complete firing. According to the interviews, all clay roof tiles below KW1 are considered low quality and represent 10% of the total results of fired roof tiles. However, determining the quality of roof tiles is not based on objective standards but rather on the visual evaluation by the craftsmen. The residents of Desa Logede mentioned that these low-quality roof tiles can still be sold at a lower price or reused by the villagers in various ways, such as for walls, garden decorations, and pathways.

Fig. 1. Production Process

4 Discussion



The case study confirms that there have been efforts to assess the quality of clay roof tiles by craftsmen, even though it is currently done subjectively. However, there is a notable discrepancy in the reported figures. According to interviews with craftsmen, only 10% of the final results of clay roof tiles are considered low quality. In contrast, on a global scale, low-quality ceramic industry products contribute to 30% of the overall ceramic industry production [5]. This difference underscores the necessity for scientific validation, such as testing methods employed by the Indonesian national standard [3]., to ascertain whether the figure mentioned by craftsmen can be substantiated.

Desa Logede has demonstrated initiatives to implement sustainable practices, such as repurposing lower-quality roof tiles for alternative functions, returning unused clay-dough to the production cycle, and alternating land use between clay extraction and farming activities. However, the effectiveness of these sustainable practices and their alignment with the principles of sustainability within the circular economy framework needs further investigation. The challenge lies in applying the circular economy concept, which requires material cycles to operate for as long as possible while maintaining environmental and economic sustainability [8]. Therefore, further studies are needed to determine the effectiveness of Desa Logede's practices in terms of sustainability.

Previous research has proven that the reuse of lower-quality roof tiles can be realized. One notable approach, termed the biological cycle, involves using these tiles as quarry filling and substrate culture. Another approach is considered a technical cycle, where lower-quality clay-roof tiles are repurposed as construction materials such as concrete aggregate, surface construction aggregate, porcelain tiles, and even building facades. However, previous studies also demonstrate that reusing the tiles not only yields positive impacts but also entails certain drawbacks [2, 13, 17]. The possibility of effectively

reusing lower-quality clay-roof tiles using the circular economy framework on a larger scale or in a more flexible manner than applied in Desa Logede still exists. However, determining the most optimal reuse method requires careful consideration of challenges and opportunities, considering the surrounding environments and the unique qualities and needs of each specific context.
Literature Review

5 Conclusion

The case study highlights subjective quality assessment discrepancies in clay roof tiles between local craftsmen and global standards. Desa Logede has shown efforts in sustainable practices, yet their effectiveness and alignment with circular economy principles require further evaluation. While previous research proves the potential for reusing lower-quality tiles, challenges and drawbacks persist. Scientific validation, comprehensive sustainability assessments, and context-specific considerations are imperative for ensuring optimal and widespread implementation of circular economy practices. Bridging the gap between local practices and global standards is essential for more sustainable and environmentally friendly clay roof tiles in Indonesia.

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