RESEARCH ARTICLE

Gate-to-Grave Life Cycle Assessment of Ceramic Tile: A Case Study of a Colombo Luxury Residence

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Abstract: This study carries out a gate-to-grave Life Cycle Assessment (LCA) of ceramic tiles to evaluate their environmental impacts in a luxury residential project in Colombo, Sri Lanka. The assessment compares manual carbon footprint calculations with results from SimaPro LCA software, encompassing the transportation, installation, usage, and disposal phases. Updated results show that the cleaning phase is the highest contributor to emissions. Manual calculations estimated 615,078.34 $kgCO_2eq$ (83.85 $kgCO_2eq/m^2$) over a 100-year lifespan, while SimaPro reported 632,197 $kgCO_2eq$. Emissions from tile production, adhesive application, and grout usage were also reassessed, with only minor differences between methods. Both approaches identified the same high-impact stages, confirming the reliability of manual methods, while SimaPro offered a more detailed impact category breakdown. Recommended sustainability strategies include switching to eco-friendly cleaning agents, recycling waste tiles into concrete aggregates, and optimizing water usage to reduce greenhouse gas emissions and resource consumption in Sri Lanka's construction sector.

Keywords: Life Cycle Assessment, Sustainability, Ceramic Tile Waste, Construction Waste, Greenhouse Gases

INTRODUCTION

A. Background of Research

The construction industry is one of the largest users of materials and energy, creating significant environmental impacts through raw material extraction, manufacturing, transportation, and waste generation. Among the many finishing materials, ceramic tiles are widely chosen because of their durability, low maintenance, and attractive appearance. However, ceramic tile production is highly energy-intensive, involving clay extraction, glazing, and high-temperature firing processes, which release large amounts of greenhouse gases (GHGs) and contribute to climate change [1].

Life Cycle Assessment (LCA) is a systematic analytical methodology for evaluating the environmental impacts of a product or process throughout its entire lifecycle. This includes looking at raw materials, manufacturing, transportation, use, and disposal [2]. In construction, LCA can identify which steps cause the most harm to the environment and help find better solutions. For ceramic tiles, LCA can show how making and wasting tiles affects the environment and suggest ways to recycle or reuse the tiles [3]. Many studies focus on the cradle-to-gate part of the LCA, which looks at environmental effects from raw material extraction to when the tile leaves the factory.

Research in Sri Lanka shows that the most energy is used during glazing and firing [4] processes. The firing process alone takes up 40% of total energy because the kilns must reach extremely high temperatures. Some studies suggest that reducing energy use by just 1% can lower CO_2 emissions significantly [5]. Earlier research on ceramic tiles focused only on the cradle-to-gate phase, which includes raw material extraction and manufacturing. However, recent studies show it is also very important to look at the entire lifecycle, including transportation, installation, long-term cleaning and maintenance, and end-of-life disposal.

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For example, [6] a cradle-to-grave Life Cycle Assessment (LCA) of glazed ceramic tiles was carried out in Spain. They found that cleaning and maintenance during the building's lifetime added a large amount to the total carbon footprint, sometimes even higher than the emissions from tile manufacturing. This is similar to the findings at selected construction sites, where cleaning the tiles over 100 years caused more than 60% of the total lifecycle emissions.

It is highlighted that firing ceramic tiles at very high temperatures (around 1200 °C) [7] using fossil fuels is the biggest source of greenhouse gas emissions in the tile lifecycle. It is also suggested that using eco-design strategies, like renewable-energy kilns and low-impact glazing, could reduce emissions by up to 20%. Similarly, a case study in China [8] showed that replacing coal-based electricity with hydropower in tile factories reduced lifecycle emissions by 98%, although problems like marine ecotoxicity from glaze chemicals remain. A wider review by Vierra [9] found that the ceramic tile industry still depends heavily on non-renewable fuels, and recycling at the end of a tile's life is very limited. The study recommended more gate-to-grave assessments that also look at installation waste, transport emissions, and disposal impacts, which are very important for large-scale projects like luxury apartments.

By quantifying emissions and proposing sustainable alternatives, the research aims to minimize impacts and support circular economy practices in the local construction sector. The assessment builds on global findings that maintenance phases, like cleaning, often dominate emissions, while installation waste exacerbates financial and environmental costs. Local challenges, such as limited recycling infrastructure, highlight the need for targeted solutions to reduce the sector's carbon footprint.

B. Aim and Objectives

This research aims to identify the environmental impact of ceramic tiles by conducting a life cycle assessment and proposing a sustainable waste management solution to minimize the overall environmental impact.

Objectives of the research are,

1. Identify the parameters required for conducting an LCA on ceramic tiles.
2. Study the life cycle of ceramic tiles, including production, use, and disposal phases.
3. Evaluate the environmental impact of ceramic tiles using LCA methodologies.
4. Propose sustainable waste management strategies for recycling and environmentally safe disposal of ceramic tiles.

METHODOLOGY

The life cycle assessment of Ceramic Tiles was done by following the steps.

A. Establish the goals and Scope
B. Conduct inventory analysis
C. Assess the Impact
D. Interpret the results

The main goal of this Life Cycle Assessment (LCA) is to evaluate how ceramic tile impacts the environment in Sri Lanka's construction industry. Construction projects generate significant amounts of tile waste due to factors like breakage, incorrect sizing, and design modifications. If this waste is not managed properly, it can lead to environmental problems such as resource depletion, energy waste, and excessive landfill use.

The scope of this study covers the life cycle of ceramic tiles, following a gate-to-grave approach. This means the research will analyze each stage of the tile's existence, from the point where the product arrives at the construction or usage site, until it is disposed of at the end of its life, ensuring a comprehensive assessment of its environmental impact.

Data were collected from the Colombo luxury residence site, including tile quantities (20,780 tiles imported, 5 percent wastage), adhesive (3,400 bags at 25 kilograms each), grout (1,000 kilograms), transport details (diesel trucks over short distances), and maintenance practices (cleaning 4 times monthly per apartment over 100 years). The functional unit was 1 square meter of ceramic tile, with a system boundary from gate-to-grave, excluding infrastructure. Life cycle inventory used field data and emission factors (Eg, Emission factor of carbon dioxide for ceramic tile was 14.4 $kgCO_2eq/m^2$, Emission factor of carbon dioxide for Adhesive was 1.2 $kgCO_2eq$). Impacts were calculated manually in Excel. Assumptions included average tile weight (3 kilograms per tile) and fuel consumption (3.3-3.5 kilometers per liter). Alternative flooring options were compared based on literature data for embodied carbon, durability, maintenance, and recyclability.

Waste quantification involved summarizing balance sheets for tiles, adhesives, and grouts. Environmental impacts were assessed across phases: tile usage, adhesives/grouts, transport, cleaning, and disposal. The key stages included in this study are:

- Transportation and Distribution - The movement of raw materials and finished tiles relies on fuel-powered transportation, mainly diesel and petrol, which contributes to carbon emissions. This study assesses how transportation impacts the environment and explores methods to optimize logistics and reduce emissions.
- Installation and Usage Phase - Ceramic tiles are durable and require little maintenance once installed. However, installation generates waste due to breakage, cutting, and incorrect sizing. This study quantifies tile waste during installation and examines how improper handling contributes to material loss.
- Waste Generation and Disposal-Large amounts of broken or unused tiles from construction projects are often discarded in landfills, contributing to waste accumulation and land occupation. This research evaluates the long-term environmental risks of tile waste disposal.
- Opportunities for Recycling and Reuse - Recycling is a more environmentally friendly option than disposing of waste in landfills. This study investigates several recycling techniques, such as breaking broken tiles for mosaics or landscaping, crushing waste tiles for use in concrete, and grinding them into powder for the creation of new tiles. Considering variables like cost, material qualities, and industry acceptance, the study also evaluates the viability of these recycling options in Sri Lanka.

A. Functional Unit

This study uses one square meter (1 m^2) of ceramic floor tile as the functional unit to precisely measure and compare environmental impacts [4]. This means that all calculations, whether related to energy consumption, raw material use, emissions, or waste generation, will be based on the impact per 1m^2 of ceramic tile and the system of the analysis is the single-fired ceramic tile with an average density of 17.23 kg/m^2. [6]

B. System Boundary

This study adopts a gate-to-grave boundary, meaning it covers all life cycle stages from the point where the product arrives at the construction or usage site, until it is disposed of at the end of its life or recycling of tile waste. However, some factors are excluded from the assessment:

- Infrastructure and Capital Goods - The environmental impact of setting up tile manufacturing plants, machinery, and transportation infrastructure is not included. This exclusion is because factories, equipment, and transport systems serve multiple production cycles and are not exclusive to ceramic tiles.
- Non-Material Emissions - Indirect environmental effects like noise pollution from machinery and aesthetic impacts of mining are not assessed. While these factors can have social and ecological consequences, they are outside the core environmental focus of this LCA.

C. Conduct Inventory Analysis

To conduct an LCA of ceramic tile waste, it is essential to collect detailed Life Cycle Inventory (LCI) data. This data provides the necessary input for the software to calculate environmental impacts, ensuring a comprehensive and data-driven sustainability analysis.

The critical data categories required for the LCA model are as follows:

I. Transportation and Distribution Data

Once ceramic tiles are manufactured, they must be transported to distribution centers and construction sites. The environmental impact of this stage is influenced by:

- Fuel consumption and emissions - The mode of transport (trucks, ships, or containers) determines the amount of diesel or gasoline used, affecting CO_2 emissions.
- Distance traveled – The total transportation distance from the factory to warehouses and construction sites directly impacts the environmental footprint.

II. Installation and Use Phase Data

The installation and usage phase considers how tiles are applied in buildings, how long they last, and whether they require maintenance.

- Material waste during installation – A certain percentage of tiles are damaged or cut during installation, adding to overall waste.
- Maintenance requirements – Ceramic tiles generally require minimal cleaning and no chemical treatments, reducing their impact in this phase.

III. End-of-Life (EOL) and Waste Management Data

At the end of their life cycle, ceramic tiles can be disposed of, recycled, or reused. Understanding how waste is managed is important for an LCA study.

- Disposal methods – Many ceramic tiles end up in landfills, which contribute to waste accumulation and land use issues.
- Recycling and reuse possibilities – Some waste tiles can be crushed and reused in construction, such as aggregates in concrete or road base material.

IV. Field Data Collection

As part of the primary research for this Life Cycle Assessment, a field visit was conducted at the construction project. The purpose of the visit was to collect real-world data on tile usage, material consumption, transport methods, installation practices, and waste management processes. This step is essential in improving the accuracy of the LCA by supplementing secondary data with first-hand observations.

During the site visit, the following key information was gathered:

- The quantity of tiles imported and used for each apartment
- Average area covered per apartment (3000 square feet)
- Tile wastage percentage during installation (approximately 5%)
- Number and type of adhesives and grouts used
- Transport distance and method (diesel trucks covering 6 km)
- Frequency of cleaning and maintenance practices per apartment

D. Impact Assessment

The LCA analysis was done by manual method and by using SimaPro Life Cycle Assessment software.

I. Impact Assessment by Manual Calculation

After collecting the required field data, a manual calculation was performed to assess the environmental impacts associated with ceramic tile use, following a gate-to-grave approach. The calculation considered emissions from different life cycle stages, including adhesive and grout usage, cleaning and water consumption, transport, and final disposal.

Table 1: Environmental impact assessment of adhesive usage

Description	Value
Weight per bag (kg)	25
Number of adhesive bags	3400
Total adhesive used (kg)	85000
Emission factor ($kgCO_2eq/kg$)	1.2
Total ($kgCO_2eq$)	102000

Table 2: Environmental impact assessment of grout usage

Description	Value
Number of Grout packets	1000
Weight per packet (kg)	1
Total Grout weight (kg)	1000
Emission factor ($kgCO_2eq/kg$)	0.8
Total ($kgCO_2eq$)	800

Table 3: Environmental impact assessment of tile transportation

Description	Value
Transport distance for tile at one time (km)	6
Number of trips to transport tiles	10
Total distance (km)	60
Fuel consumption	3.3km/ L
Total fuel used (L)	18.18
Emission factor ($kgCO_2eq/L$)	3.12
Total ($kgCO_2eq$)	56.73

Table 4: Environmental impact assessment of adhesive transportation

Description	Value
Transport distance for adhesive at one time (km)	1.5
Number of trips to transport adhesive	20
Total distance (km)	30
Fuel consumption	3.5km/L
Total fuel used (L)	8.57
Emission factor ($kgCO_2eq/L$)	3.12
Total ($kgCO_2eq$)	26.24

Table 5: Environmental impact assessment of the cleaning phase

Description	Value
Cleaners per apartment per month (L)	1
Number of apartments	121
Cleaners per year (L)	1452
Lifespan(years)	100
Total cleaners(L)	145200
Density (kg/L)	1
Total weight (kg)	145200
Emission factor($kgCO_2eq/kg$)	2.8
Total CO_2eq from cleaning phase (kg)	406560

Table 6: Environmental Impact Assessment of Tile Disposal after usage at the End of Life

Description	Value
Number of tiles	19741
Total area (m^2)	7335.4
Tile emission factor ($kgCO_2eq/m^2$)	14.4
Total CO_2eq (kg)	105634.87

The manual calculations for each inventory data are performed, and the total environmental impact was calculated according to Table 7.

Impact Assessment by Sima Pro LCA Software

Impact Assessment of the SimaPro is carried out following the steps below.

1. Generation of Tree
2. Characterization
4. Normalization
5. Weighting
6. Single Score

Table 7: Total Environmental Impact from Manual Calculation

Description	Value
Adhesive usage emissions ($kgCO_2eq$)	102000
Grout usage emissions ($kgCO_2eq$)	800
Transportation emissions ($kgCO_2eq$)	83.47
Cleaning phase emissions ($kgCO_2eq$)	406560
Disposal emissions ($kgCO_2eq$)	105634.87
Total $kgCO_2eq$	**615078.34**
Per Functional Unit	
Usable tile area (m^2)	7335.4
Total $kgCO_2eq$ per m^2 over 100 years	83.85

RESULTS

A. Impact Assessment by Manual Calculation Method

The ceramic tile at the selected construction generates approximately 615078.34 $kgCO_2eq$ over a 100-year lifespan, equivalent to 83.85 $kgCO_2eq$ per m^2 of 7,335.4 m^2 usable tiled area. This carbon footprint represents the total greenhouse gas emissions, including Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O), contributing to global warming across the tile's lifecycle, from construction usage to disposal. This significant Impact underscores the need for sustainable practices to reduce environmental harm in Sri Lanka's construction industry. The emissions are distributed across various lifecycle phases. The environmental impact of ceramic tile use over its full life cycle can be categorized into high, moderate, and low impact stages based on total CO_2 emissions. The highest environmental impact comes from the cleaning phase, which contributes 406,560 $kgCO_2eq$ to 66.1% of total life cycle emissions. This high value is mainly due to the continuous use of tile cleaners and water for over 100 years across 121 apartments. Any phase contributing over 40% of total emissions is considered to have a high impact in this analysis. Final disposal of tiles at the end of the life disposal contributes 105634.87 $kgCO_2eq$, or 17.2% of total emissions. There is still an opportunity for development through better material planning and recycling. Stages with emissions between 10% and 40% are considered moderate in this context. Another moderate impact stage is adhesive usage, which adds 102,000 $kgCO_2eq$ or 16.6% of emissions. The energy-heavy chemical processes involved in manufacturing adhesives significantly affect the project's carbon footprint. Transportation contributes only 83.47 $kgCO_2eq$, or 0.01%, and is considered very low impact. This is due to the short distances between the factory and the construction site. Similarly, grout usage results in just 800 $kgCO_2eq$, representing 0.1% of total emissions, making it another very low-impact phase. Finally, the total impact of 83.85 kg CO_2eq/m^2 provides a benchmark for comparing the project's sustainability with other construction projects in Sri Lanka.

B. Impact Assessment Using Sima Pro Software

The network diagram in Figure 1, it is notice that there is one colored arrow, which is red; when the arrows get thicker, it means the environmental impact of the category also increases. In the Analysis method of IPCC GWP 100a, which is used to identify the climate changes under the Intergovernmental Panel on Climate Change (IPCC) for 100 years. The amount of heat that a greenhouse gas retains in the atmosphere over a given time in relation to carbon dioxide (CO_2eq) is known as the global warming potential (GWP). The global warming potential (GWP) of greenhouse gases (GHGs) over 100 years was evaluated in this study using the characterization model for mid-point assessment. According to the tree diagram, the Total Global Warming produced by the analysis of ceramic tiles, the Gate-to-Grave approach is 6.32×10^5 $kgCO_2eq$. The tree diagram can be seen that the Forming agent, which is used in the cleaning phase, has the most significant potential impact (3.70×10^5 kg CO_2eq) on global warming, equivalent to 57.4% of total life cycle emissions. A moderate percentage of 20.1% of Impact assessed from Adhesive Mortar, that equivalent to 1.30×10^5 $kgCO_2eq$ and 7.90 $kgCO_2eq$ generated as greenhouse gases from Ceramic tile usage. The Disposal of the broken tile as Municipal solid waste generated GWP values is 8.15×10^4 kg CO_2eq. The transportation processes are not shown in the diagram because to are applied as the Process stage of ceramic tile installation. These include all the details in the SimaPro Ecoinvent 3.0 update database.

C. Comparative Analysis with International LCA Studies

The results of this study align closely with international research on ceramic tile lifecycle impacts. The findings that the cleaning phase contributes the highest proportion of lifecycle emissions (66.1% manually, 58.5% via SimaPro) are consistent with European studies. For instance, [6] reported that the use phase, particularly cleaning operations, accounted for approximately 60% of total environmental impacts in Spanish ceramic tile installations over 50 years. Similarly, in a previous study [8] it was found that post-installation maintenance contributed 55-65 % of lifecycle greenhouse gas emissions, predominantly due to chemical cleaning agents and water heating requirements. The adhesive usage contribution observed in this study (16.6-20.4 %) is comparable to Italian research findings, where mortar and adhesive applications represented 15-18 % of total embodied carbon in tile installations [18]. The relatively low transportation impact (0.01-0.22 %) in the current study is attributed to short supply chain distances in Sri Lanka, contrasting with European studies where transportation typically accounts for 3-5 % of total impacts due to longer distribution networks. The total gate-to-grave carbon footprint of 83.85 $kgCO_2eq/m^2$ over 100 years is moderately higher than the European average of 65-75 $kgCO_2eq/m^2$ reported for similar functional units, potentially reflecting differences in energy sources, cleaning frequencies, and climatic conditions requiring more intensive maintenance in tropical environments. However, when normalized to a 50-year lifespan for direct comparison with international studies, the impact reduces to approximately 41.9 $kgCO_2eq/m^2$, which falls within the global range of 35-50 $kgCO_2eq/m^2$ for ceramic tile installations in residential buildings. These comparisons validate the methodology employed in this study while highlighting regional variations in lifecycle impacts, particularly in the cleaning phase, which appears more significant in tropical climates compared to temperate regions.

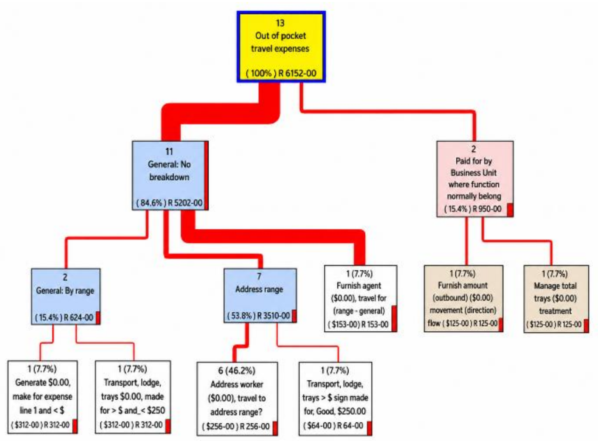

Figure 1: Network Diagram of Gate to Grave Analysis using SimaPro

D. Results interpretation of manual calculation and Semipro software results

The environmental effects from manual calculations were compared with SimaPro results to assess consistency and accuracy, as in Table 8. In addition to emphasizing important impact categories and the processes that contribute to them, this interpretation seeks to assess the consistency and differences between the two approaches, offering insights into the precision and dependability of the life cycle assessment for ceramic tile production.

Table 8: Comparative Analysis of Manual Calculation and SimaPro LCA Results.

Phase	Total $kgCO_2eq$ Manual Method	Percentage of Total Manual Method (%)	Total $kgCO_2eq$ Sima Pro Software	Percentage of Total SimaPro (%)
Adhesive usage	102000	16.6	129000	20.4
Grout usage	800	0.1	281	0.05
Transportation	83.47	0.01	1397	0.22
Cleaning phase	406560	66.1	370000	58.5
Tile usage and disposal	105634.87	17.2	131519	20.8
Total $kgCO_2eq$	615078.34	100	632197	100

Adhesive Usage:

The manual calculation gives 102,000 $kgCO_2eq$ (16.6%), but SimaPro shows 129000 $kgCO_2eq$ (20.4%). This variation may happen because SimaPro includes a broader scope, such as raw material extraction and curing process emissions, which may not be fully included in the manual calculation.

Grout Usage:

Manual calculation reports 800 $kgCO_2eq$ (0.1%), while SimaPro shows 281 $kgCO_2eq$ (0.05%). The lower SimaPro value might be due to a more conservative estimate of cement mortar emissions, possibly leaving out minor secondary impacts that the manual method considered.

Transportation:

Manual calculation gives 83.47 $kgCO_2eq$ (0.01%), while SimaPro shows 1,397 $kgCO_2eq$ (0.22%). The higher SimaPro value suggests it accounts for more detailed transport emissions, such as longer supply chains and additional logistics impacts, which the manual approach may not fully include.

Cleaning Phase:

Manual calculation shows 406,560 $kgCO_2eq$ (66.1%), while SimaPro reports 370,000 $kgCO_2eq$ (58.5%). The slight difference may come from different modeling of foaming agent impacts, where the manual method might overestimate usage or energy demand compared to SimaPro's market-based assumptions.

Tile Usage and Disposal:

Manual calculation indicates 105634.87 $kgCO_2eq$ (17.2%), while SimaPro records 131519 $kgCO_2eq$ (20.8%). The slight difference might suggest that the Simapro calculation considered extra factors. In summary, Manual calculation was done according to estimated and collected data, referring to research articles and pointing out the emission factors related to the phases and materials. So manual calculation might have some misrepresented data and limitations. But SimaPro is more accurate and efficient software that includes Global Databases and accurate actors, especially for Life Cycle Assessment. SimaPro, using the ReCiPe midpoint method, IPCC GWP 100 method, and Ecoinvent database, includes detailed life-cycle inventories, such as upstream raw material extraction, transport logistics, and long-term landfill emissions. So, it provided more reliable results than manual calculation without input errors. But Simapro also has limitations due to the Demo version the percentages as it includes data.

E. Alternative Floor Finishing Solutions

Ceramic tiles require substantial energy for glazing and high-temperature kiln firing, resulting in elevated carbon emissions across their lifecycle from transportation through installation to disposal. Among the alternative flooring materials evaluated, engineered wood, bamboo, linoleum, cork flooring, polished concrete, and terrazzo demonstrate superior environmental performance with significantly lower gate-to-grave carbon emissions.

Polished concrete uses the existing concrete slab in a building as the final flooring. It is finished by grinding, polishing, and sealing, so no extra flooring materials or adhesives are needed. Because it reuses what is already there, it has one of the lowest embodied carbon footprints (3–5 $kgCO_2eq/m^2$) [10]. It is also very durable, lasting more than 50 years with almost no maintenance. This means fewer repairs and less waste of time. Polished concrete can also help keep buildings cooler in warm climates because it acts as a thermal mass, storing heat and reducing cool energy. However, it can feel hard and cold underfoot, so rugs may be needed for comfort. It also needs skilled workers to achieve a smooth, high-quality finish.

Terrazzo is a decorative flooring made from recycled marble, glass, or stone chips mixed with cement or epoxy binder, then polished. Unlike ceramic tiles, it does not require energy-intensive kiln firing, which makes it 50–60% less energy-demanding [11]. It usually contains 60–80% recycled content, helping to reduce waste and support the circular economy [12]. Terrazzo is extremely long-lasting (50+ years) and easy to clean because it is non-porous, so it does not trap stains or bacteria. It also produces low or zero VOCs, which improves indoor air quality [13]. The downside is that terrazzo has a higher upfront cost, and like concrete, it feels cold and hard unless underlay or rugs are used.

Linoleum is made from natural, renewable materials like linseed oil, wood flour, cork dust, and jute backing. It is biodegradable and compostable at the end of its life, so it doesn't create landfill waste [10]. It has a low embodied carbon (4–6 $kgCO_2eq/m^2$) and can last 20–40 years if cared for properly [12]. Linoleum is naturally anti-bacterial and hypoallergenic, making it great for healthy indoor spaces. It also feels softer and warmer underfoot than concrete or terrazzo. However, it needs careful installation to avoid cracking and sometimes requires waxing or sealing to keep its protective surface.

Bamboo is a fast-growing, renewable grass that reaches maturity in just 3–5 years, making it much more sustainable than slow-growing hardwood [14]. Bamboo flooring is strong and moisture-resistant, even harder than oak in some cases. It has a moderate carbon footprint (6–9 $kgCO_2eq/m^2$). However, most bamboo is imported from Asia, which adds transport emissions. Some bamboo flooring is made with formaldehyde-based adhesives, which can release VOCs. It's better to choose low-emission certified products [15]. Bamboo flooring lasts 25–30 years but may scratch more easily than hardwood.

Engineered wood has a thin hardwood veneer on top of layers of wood. It uses less raw wood than solid hardwood and stores carbon while the trees are growing. Its embodied carbon (7–10 $kgCO_2eq/m^2$) is moderate [16]. Good-quality engineered wood can be sanded and refinished several times, so it can last 30–50 years. It is also more stable than solid hardwood, meaning it won't warp or expand easily. To make it more sustainable, it's important to choose FSC-certified wood and low-VOC adhesives. The downside is that manufacturing uses more energy than bamboo or linoleum, which raises its overall carbon footprint. Cork comes from the bark of cork oak trees, which can be harvested every 9–12 years without cutting down the tree. This makes it a renewable resource [17]. Cork flooring provides natural thermal and sound insulation, is resistant to mold and pests, and is biodegradable at the end of its life. It has a low embodied carbon (5–7 $kgCO_2eq/m^2$) and feels soft and comfortable underfoot, which makes it ideal for living spaces. However, cork needs sealing to protect it from moisture, and it can dent under heavy furniture. It usually lasts 20–25 years.

Table 9: Comparative Environmental Performance of Alternative Floor Finishing Solutions

Flooring Type	Embodied Carbon ($kgCO_2eq/m^2$)	Recycled/ enewable	Durability (years)	Maintenance	End-of-Life
Polished Concrete	3–5 (very low)	Uses existing slab	50+	Very low	Fully reusable
Terrazzo	5–8 (50–60% lower than ceramic)	60–80% recycled chips	50+	Very low	Recyclable
Linoleum	4–6 (low)	100% renewabl e	25–40	Low	Compostable
Bamboo Flooring	6–9 (moderate)	Fast renewabl e grass	25–30	Low	Partly recyclable
Engineered Wood	7–10 (moderate)	30–50% recycled core	30–50	Low	Reusable

F. Limitations and Assumptions

This study acknowledges several limitations that should be considered when interpreting the results. First, the manual calculation methodology relies on emission factors derived from international databases and published literature, which may not fully capture the specific conditions and technologies used in Sri Lankan ceramic tile production and installation. The emission factor for ceramic tiles (14.4 $kgCO_2eq/m^2$) was adopted from regional studies and may vary depending on kiln technology, fuel sources, and manufacturing efficiency.

Second, the system boundary excludes infrastructure impacts, including the environmental footprint of manufacturing facilities, machinery, and transportation infrastructure. While this exclusion is common practice in LCA studies to avoid allocation complexities, it may underestimate the total environmental burden, particularly for short-lived projects where infrastructure impacts are more significant per functional unit.

Third, the study assumes uniform cleaning practices across all 121 apartments over the 100-year lifespan, with constant cleaner consumption rates (1 liter per apartment per month). Maintenance practices may vary significantly based on occupant behavior, socioeconomic factors, and evolving cleaning technologies. This assumption may overestimate or underestimate actual cleaning-phase impacts.

Fourth, the manual calculations assume average tile weight (3 kg per tile) and standard fuel consumption rates (3.3-3.5 km/L) for transportation. Variations in tile specifications, vehicle efficiency, and load capacity could affect the accuracy of transportation impact estimates. The SimaPro analysis, while more comprehensive, is limited by the demo version constraints and the availability of region-specific data in the Ecoinvent 3.0 database, necessitating the use of proxy data from similar geographic contexts.

Fifth, the end-of-life disposal scenario assumes landfilling as the primary waste management route, reflecting current practices in Sri Lanka. However, emerging recycling technologies and circular economy initiatives could significantly alter future disposal impacts. The study does not account for potential carbon sequestration in recycled applications or the avoided burdens from material substitution.

Finally, scope exclusions such as worker health impacts, noise pollution, aesthetic environmental effects, and indirect land-use changes were necessary to maintain focus on greenhouse gas emissions, but limit the comprehensiveness of the environmental assessment. Future research incorporating broader impact categories, regional emission factors, and dynamic lifecycle modeling would enhance the robustness and applicability of LCA findings for Sri Lankan construction contexts.

CONCLUSION

This research is the first gate to grave life cycle analysis of Ceramic Tiles in Sri Lanka. The Life Cycle Assessment found that the cleaning phase is the largest source of environmental impact for ceramic tiles. Manual calculations estimated 615078.34 $kgCO_2eq$ over 100 years (83.85 $kgCO_2eq/m^2$), while SimaPro software gave 632197 $kgCO_2eq$. In both methods, cleaning contributed over 50% of total emissions due to the long-term use of chemical cleaners. Tile production, adhesive application, and grout usage followed with small differences between methods. Manual calculations provided reliable total results, while SimaPro offered a more detailed impact category breakdown (eutrophication, acidification, particulate matter formation, fossil fuel depletion). The findings show that reducing cleaning frequency, using eco-friendly cleaning agents, recycling waste tiles into concrete aggregates, and sourcing low-carbon, locally made materials can reduce greenhouse gas emissions and resource use, improving environmental sustainability in Sri Lanka's construction sector.

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