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A Carbon Footprint Assessment for Building Ceramics from the Life Cycle Perspective: A Case Study in Eastern China

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Abstract

The product carbon footprint quantifies the greenhouse gas (GHG) emissions throughout the life cycle of a product. In this study, the carbon footprint of building ceramics produced in eastern China has been estimated, following the life cycle assessment methodology and the actual production data. The calculation boundary includes raw materials extraction, raw materials transportation and building ceramics production. The carbon footprint of building ceramics is 6.386 kg CO_2 per square metre. The contribution of every process has also been identified. The manufacturing stage accounts for 63.25% of the total carbon footprint. The remaining processes collectively account for less than 40%. Several measures to reduce the carbon footprint have been suggested, including substituting coal with other fuels, establishing a gas pressure control system, applying low-temperature fast-firing technology, using microwave drying, adopting a wet-milling-free process, etc. Finally, the importance of developing new ceramic raw materials is emphasized.

Keywords

Building Ceramics, Life Cycle, Carbon Footprint

1. Introduction

Climate change has become one of the most relevant global challenges. One way to combat climate change is to calculate and then reduce the climate impacts of a single product. The carbon footprint of a product is an estimate of the total greenhouse gas (GHG) emissions over its life cycle, representing its contribution to climate change [1] [2]. A comprehensive life-cycle carbon footprint assessment is essential to pinpoint emission sources across the product value chain and to develop efficient, targeted climate mitigation strategies at the product level. Product carbon footprint (PCF) also enables the comparison of the climate impact of competing building materials, such as building ceramics sourced from different countries but sold in the same market.

The manufacturing of building ceramics is a highly energy-intensive process and a significant source of carbon emissions, as it involves multiple stages where the products must undergo thermal treatment. Particularly, the forming and sintering processes of ceramics demand high-temperature kilns, which consume substantial amounts of fuel and electricity, making them carbon-intensive phases [3]. And research shows the production of ceramic tiles represents approximately 2% of China's total industrial energy consumption and carbon emissions each year [4]. The output of building ceramics reached 5.91 billion square meters in 2024. Given this substantial output, the sector faces significant pressure to reduce its carbon emissions.

Many studies have focused on carbon emissions from industries like electricity generation [5] [6], iron and steel [7] [8], copper [9], etc. However, research on the carbon footprint in the field of building ceramics remains limited. Based on data collected from two ceramic factories in Yunnan Province between November 2020 and May 2021, Yang Li *et al.* [10] have calculated that the carbon emission intensity of pottery production is 1.91 kg CO_2 per kg of product. The life cycle distribution of these emissions is as follows: raw material extraction accounted for 6.9%, raw material transportation for 4%, and the production process for 89.1%. Research has shown that utilizing industrial waste fly ash as a substitute for potassium feldspar in ceramic tile production can reduce the climate change impact by 8% [11]. Furthermore, in a study, strategies such as partial replacement of virgin raw materials with waste, kiln waste heat recovery, and replacing conventional energy sources with clean alternatives have demonstrated a potential reduction in the global warming potential of ceramic tile production by 21.36% [12]. This paper presents a life cycle assessment of carbon emissions from the building ceramics industry in East China. It further provides a comprehensive analysis of emission reduction pathways and their prospective environmental benefits.

2. Methodology

This study intends to quantify the carbon footprint of building ceramics produced in eastern China, following the life cycle theory.

2.1. Research Scope

In order to collect relevant information and data, seven building ceramics manufacturers located in eastern China have been investigated. And the data used to calculate was mean value. Building ceramics serve as a raw material in the construction industry. So a cradle-to-gate system boundary is adopted for this study. The functional unit was defined as one square meter. And it considered carbon dioxide emissions only in this paper.

2.2. Data Collection

According to system boundary, the data that should be collected comprises raw material acquisition data, transportation data, and production data. Data for the transportation and production unit processes were collected directly from the ceramic mill, whereas data for the raw material acquisition unit were obtained from published literature and other sources.

2.3. Carbon Emissions Calculation Model

Figure 1 shows the kinds of carbon emissions in the product life cycle. The carbon emissions can be categorized into two types: direct and indirect emissions. Carbon emissions from combustion refer to those generated by fossil fuel combustion (e.g., coal, natural gas, and diesel), whereas emissions from carbonates encompass CO_2 released from the decomposition of materials like limestone during calcination.

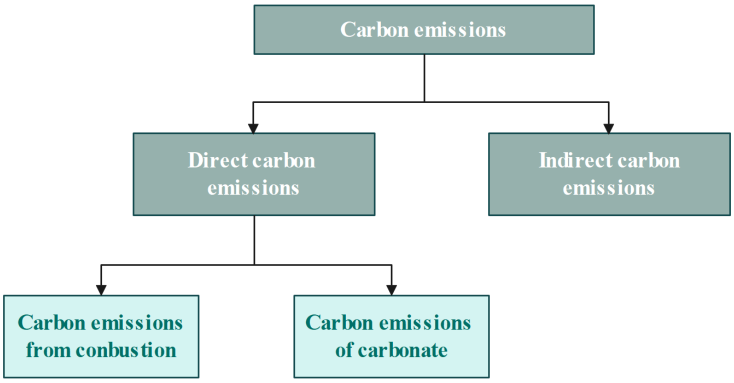

Figure 1. Carbon emissions kinds in product life cycle.

The quantity of carbon emissions from combustion can be calculated using the following Equation (1).

$$C_f = \sum_{i=1}^{n} M_i \cdot E_i \cdot Q_i \cdot R_i \cdot \frac{44}{12} \tag{1}$$

In the equation, C_f denotes the carbon emissions from combustion, M_i represents the consumption of ith fuel, E_i is the lower calorific value of ith fuel, Q_i is the carbon content per unit calorific value of ith fuel, R_i is the oxygenation efficiency of ith fuel, and n represents the total number of fuel types.

Carbon emissions of carbonate can be calculated by Equation (2).

$$C_p = \sum_{j=1}^{m} M_j \cdot F_j \tag{2}$$

where C_P is carbon emissions of carbonates during calcination, M_j is the quantity of jth carbonate consumed, F_j is the emission factor of jth carbonate, and m is the total number of carbonates.

And indirect carbon emissions can be calculated by Equation (3).

$$C_E = \sum_{k=1}^{r} M_k \cdot F_k \tag{3}$$

where C_E is indirect carbon emissions, M_k denotes the amount of electricity or heating power consumed, and F_k is the corresponding emission factor.

3. Results and Discussion

3.1. Inventory Analysis

3.1.1. Mining of Raw Materials

The production of building ceramics employs a variety of raw materials, which can be broadly categorized into plastic materials, desert materials, flux materials and auxiliary chemical materials. Due to their minor dosage, auxiliary chemical materials were excluded from the assessment. Since mining characteristics and associated carbon emissions are similar for materials of the same type, a representative material is selected for each category. Kaolin is selected to represent plastic materials, quartz represents desert materials, and feldspar represents flux materials. Because limestone releases CO_2 during calcination, it is treated separately in the assessment. Data on raw material extraction are presented in **Table 1**.

Table 1. Energy consumption in raw materials exploitation.

Unit process	Anthracite, kg/kg	Crude oil, kg/kg	Natural gas, m^3/kg
Kaolin [a]	3.92E−03	4.00E−02	3.25E−04
Feldspar [b]	--	3.47E−03	--
Quartz [c]	1.73E−04	5.48E−03	6.65E−04
Limestone [b]	--	3.47E−03	---

Data source: a. Reference [13]; b. Simapro software database; c. GaBi software database.

As shown in **Table 1**, anthracite, crude oil and natural gas are consumed in raw materials exploitation. The default values of associated parameters are listed in **Table 2**.

Table 2. Default parameter values for fossil fuels.

Fossil fuel	Lower calorific value	Carbon content per unit calorific value	Oxygenation efficiency
Anthracite	2.287E−02 TJ/t [d]	27.4 t-C/TJ [d,e]	94% [d,e]
Crude oil	4.182E−02 TJ/t [f]	20.1 t-C/TJ [d,e]	98% [d,e]
Diesel	4.265E−02 TJ/t [f]	20.2 t-C/TJ [d,e]	98% [d,e]
Natural gas	3.893E−05 TJ/ m^3 [f]	15.3 t-C/TJ [d,e]	99% [d,e]

Data source: d. GB/T 32151.40-2025 Requirements of the greenhouse gas emissions accounting and reporting—Part 40: Building waterproof materials enterprises; e. Guidelines for the Compilation of Provincial-Level Greenhouse Gas Inventories in China (Interim); f. China Energy Statistical Yearbook 2023.

The carbon emission values, calculated with Equation (1) and the parameters in Table 1 and Table 2, are presented in Table 3. Specifically, they are 0.129 kg CO_2/kg for kaolin, 0.0105 kg CO_2/kg for feldspar, 0.0169 kg CO_2/kg for quartz, and 0.0105 kg CO_2/kg for limestone.

Table 3. Carbon emissions in raw materials production.

Raw materials	Kaolin	Feldspar	Quartz	Limestone
Carbon emission, kgCO_2/kg	1.29E−01	1.05E−02	1.69E−02	1.05E−02

3.1.2. Raw Materials Transportation

Raw materials used for building ceramics production are sourced from various regions across China. Table 4 shows the transportation data for raw materials, based on the actual procurement details.

Table 4. Raw materials transportation data.

Raw material	Mode of transport	Shipping distance, km
Clay strips	River transport	800
Pyrophyllite	Land carriage	200
White mud	Land carriage	200
Kaolin	Land carriage	200
Bentonite	River transport	1200
Clay	River transport	1200
Feldspar	Land carriage	350
Pyroxene	River transport	1000
Wollastonite	Land carriage	200
Talc	River transport	900
Quartz	River transport	450
Limestone	River transport	900

Table 5 presents the carbon emission factors for different transportation modes [14].

Table 5. Emission factors for different transportation modes.

Mode of transport	Emission factor, kgCO_2/kg·km
Land carriage (gasoline car)	1.81E−04
Land carriage (diesel vehicle)	1.22E−04
River transport	4.11E−05
Maritime transport	1.90E−05

3.1.3. Production Process

The production process of building ceramics comprises batching, ball milling, spray drying, molding, firing, etc. Raw materials and energy consumption for producing 1 m^2 of building ceramics are shown in **Table 6** and **Table 7**. The carbon emission from raw materials exploitation, derived from **Table 3** and **Table 6**, is 1.678 kg CO_2.

Table 6. Resource consumption for 1 m^2 building ceramics production.

Raw material	Consumption, kg
Clay strips	0.688
Pyrophyllite	1.318
White mud	0.328
Kaolin	2.848
Bentonite	0.222
Clay	7.105
Feldspar	2.002
Pyroxene	0.345
Wollastonite	0.208
Talc	0.087
Quartz	1.475
Limestone	1.085

Table 7. Energy consumption for 1 m^2 of building ceramics production.

Energy	Electricity, kWh	Natural gas, m^3	Diesel, kg	Anthracite, kg
Consumption	1.763	1.059	0.011	1.161

By integrating the aforementioned data, carbon emissions from raw materials transportation for 1 m^2 building ceramics are calculated to be 0.669 kg. Carbon emissions from the production process comprise two components: those originating from energy consumption and those resulting from carbonate calcination. The emission factors for electricity and limestone are given in **Table 8**. So carbon emissions for building ceramics production are 3.562 kg/m^2. Moreover, carbon emissions of limestone calcining are 0.477 kg. Thus the carbon emissions in production are 4.039 kg. Therefore, following the calculation methodology outlined above, carbon footprint of building ceramics is 6.386 kg CO_2/m^2.

Table 8. Emission factors of relevant parameters in the production process.

Parameter	Emission factor
Electricity	0.5777 kg CO_2/kWh [g]
Limestone	0.4397 kgCO_2/kg [h]

Data source: g. 2024 China grid electricity emission factor; h. GB/T 32151.35-2025 Requirements of the greenhouse gas emissions accounting and reporting—Part 35: Glass fibre products enterprises.

3.2. Improvement Measures

The energy consumption and carbon emissions from building ceramics production in China are higher than the international advanced level. That means it is really urgent to reduce carbon emissions in building ceramics industry.

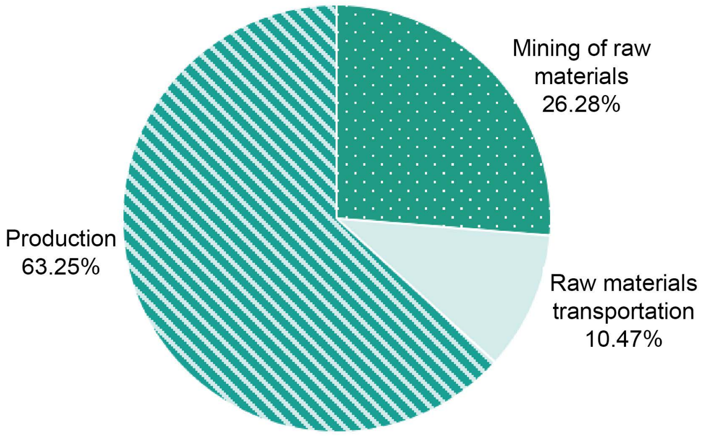

Figure 2. Proportion of carbon emissions in every stage.

The fundamental approach to carbon reduction begins with identifying the primary emission sources, followed by the application of targeted abatement technologies. Proportion of carbon emissions in every stage is presented in **Figure 2**. It can be seen that production phase constitutes the primary source of carbon emissions, accounting for 63.25% of the total life-cycle carbon emissions. Consequently, the adoption of targeted measures during the production phase would facilitate substantial carbon emission mitigation.

In the production process, fuel switching from coal to diesel oil or natural gas is a good way to reduce carbon emissions. Compared with coal, natural gas has a lower emission factor, thus it can be used to reduce annual carbon emissions. For the same reason, if coal is substituted for diesel oil, the annual emissions will be reduced, too. At this point, efforts should be directed toward developing strategies to substitute coal with natural gas or diesel oil in building ceramics production.

Additionally, a gas pressure control system in the kilns/shuttle kilns can be used to reduce carbon emissions [15]. This creates an air curtain that prevents combustion gases from being released into the atmosphere, thereby maintaining constant pressure inside the kiln. Such stable pressure conditions help reduce natural gas consumption. So this improvement measure can result in a decrease in carbon emissions.

By applying low-temperature fast-firing technology to reduce firing temperature and the cycle time, energy consumption can be decreased, thereby reducing carbon emissions. The application of low-temperature fast-firing technology resulted in a reduction of approximately 20 minutes in the firing cycle and a corresponding 30% decrease in energy consumption. Consequently, this results in a significant decrease in carbon emissions.

Microwave drying is another energy-saving technology, thereby achieving reduced carbon emissions. This method enables simultaneous internal and external heating of materials and significantly accelerates moisture removal, which greatly enhances production efficiency and thus lowers the carbon footprint of the drying process.

To address the high energy consumption in ceramic raw material ball milling, a wet-milling-free process can be adopted. Combined with the replacement of conventional energy sources with water gas, this process achieves a calcination temperature below 1200˚C, reduces the calcination time by 20%, and lowers energy consumption by 40%.

If afterheat is recycled in the process, fuel consumption can be reduced and carbon emissions will be lowered as well. Therefore, afterheat recycling is also an effective method to reduce carbon emissions.

Finally, as the ceramic market continues to expand, high-quality ceramic resources are becoming increasingly scarce. Guangdong previously had abundant clay resources, but these have now become increasingly rare. Currently, clay resources are often imported from abroad, such as from Ukraine. Although carbon emissions from raw materials extraction may appear modest, those from long-distance transportation cannot be ignored. Developing new ceramic raw materials will be a key focus of future research work.

4. Conclusion

The scope of the calculation method shown in this paper includes raw materials exploitation, raw materials transportation and production process. Using this method, the carbon footprint of building ceramics is determined as 6.386 kg/m^2. The proportion of carbon emissions from raw materials exploitation, raw materials transportation, and production is 26.28%, 10.47%, and 63.25%, respectively, and building ceramics production is the main carbon emissions process. Therefore, special attention should be directed to the production process. Several methods can be employed to reduce carbon emissions, including substituting coal with other fuels, establishing a gas pressure control system, applying low-temperature fast-firing technology, utilizing microwave drying, adopting a wet-milling-free process, etc. Furthermore, developing new ceramic raw materials is also crucial. These obtained results might provide valuable information for further development of manufacturing building ceramics with lower CO_2 emissions.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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