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Carbon Footprints of Precast Construction: A Case Study of Two-Storey House in Thailand

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ABSTRACT

The construction industry significantly contributes to global carbon dioxide (CO_2) emissions, underscoring the need to evaluate the environmental performance of modern construction systems such as precast technology. This study assesses the CO_2 emissions associated with a two-storey residential precast building in Thailand. Emissions were evaluated from three major sources: construction materials, transportation of materials, precast components, labour and waste, and energy consumption during both off-site precast manufacturing and on-site construction activities. The total CO_2 emission intensity was 175.58 $kgCO_2/m^2$. Construction materials were the dominant contributor, accounting for 145.67 $kgCO_2/m^2$ (83%). Energy consumption contributed 21.85 $kgCO_2/m^2$ (12%), and transportation activities represented the smallest share at 8.06 $kgCO_2/m^2$ (5%). These findings indicate that the environmental performance of precast construction is primarily influenced by construction materials and energy use. Therefore, reducing emissions in precast systems requires strategies such as adopting low-carbon and alternative materials, improving factory energy efficiency, increasing the use of renewable electricity, and optimizing logistics for material and precast component transportation. Overall, the results provide practical insights to support low-carbon precast construction and contribute to sustainable construction practices in Thailand and similar contexts.

Keywords: *Carbon dioxide emission, Precast construction, Construction materials, Energy use, Transportation*

ထိုင်းနိုင်ငံရှိ Precast Construction ဆောက်လုပ်ရေးနည်းလမ်းအသုံးပြု၍ နှစ်ထပ်မြင့် အိမ်ဆောက်လုပ်ခြင်းမှ ထွက်ရှိသည့် ကာဗွန်ခြေရာများအား လေ့လာဆန်းစစ်တွက်ချက်ခြင်း

ခင်ထက်ထက်ထွန်း၊ ဦးစီးအရာရှိ

စာတမ်းအကျဉ်း

ဆောက်လုပ်ရေးလုပ်ငန်းကဏ္ဍသည် ကမ္ဘာလုံးဆိုင်ရာကာဗွန်ဒိုင်အောက်ဆိုဒ်ထုတ်လွှတ်မှုတွင် သိသာထင်ရှားစွာ ပါဝင်သောကြောင့် Precast နည်းပညာကဲ့သို့သော ဆောက်လုပ်ရေးစနစ်များ၏ ပတ်ဝန်းကျင်ဆိုင်ရာစွမ်းဆောင်ရည်ကိုလေ့လာရန် လိုအပ်ပါသည်။ ဤလေ့လာမှုသည် Precast နည်းလမ်းဖြင့် ဆောက်လုပ်ထားသည့် ထိုင်းနိုင်ငံရှိ လူနေအိမ်နှစ်ထပ်အဆောက်အအုံဆောက်လုပ်ခြင်းမှ ထွက်ရှိသည့် ကာဗွန်ဒိုင်အောက်ဆိုဒ်ဓာတ်ငွေ့ (CO_2) ထုတ်လွှတ်မှုများကို လေ့လာဆန်းစစ်ခဲ့ခြင်းဖြစ်ပါသည်။ CO_2 ထုတ်လွှတ်မှုများကို အဓိကရင်းမြစ် ၃ ခု ဖြစ်သည့် ဆောက်လုပ်ရေး ပစ္စည်းများ၊ စွန့်ပစ်ပစ္စည်း၊ အလုပ်သမား၊ Precast အစိတ်အပိုင်းများနှင့် ဆောက်လုပ်ရေးပစ္စည်းများ သယ်ယူပို့ဆောင်ခြင်း၊ အိမ်ဆောက်မည့်နေရာတွင် ဆောက်လုပ်ရေး လုပ်ငန်းဆောင်ရွက်ခြင်းနှင့် Precast အစိတ်အပိုင်း ထုတ်လုပ်ခြင်းတို့အတွက် စွမ်းအင်သုံးစွဲခြင်း တို့မှ လေ့လာဆန်းစစ်ခဲ့ပါသည်။ တွက်ချက်မှုရလဒ်များအရ စုစုပေါင်း CO_2 ထွက်ရှိမှုမှာ175.58 $kgCO_2/m^2$ ဖြစ်ကြောင်း လေ့လာတွေ့ရှိခဲ့ရပါသည်။ ဆောက်လုပ်ရေး ပစ္စည်းများမှ 145.67 $kgCO_2/m^2$ (83%) ဖြင့် ထုတ်လွှတ်မှုများအနက် အများဆုံးဖြစ်ကြောင်း တွေ့ရှိခဲ့ရပါသည်။ ဆောက်လုပ်ရေးလုပ်ငန်း ဆောင်ရွက်မှုများနှင့် Precast အစိတ်အပိုင်းထုတ်လုပ်ခြင်းတို့အတွက် စွမ်းအင်သုံးစွဲခြင်းတို့မှ 21.85 $kgCO_2/m^2$ (12%) ထွက်ရှိခဲ့ပြီး သယ်ယူပို့ဆောင်ခြင်းများမှ 8.06 $kgCO_2/m^2$ (5%) ဖြင့် CO_2 အနည်းဆုံးထွက်ရှိခဲ့ကြောင်း လေ့လာ သိရှိခဲ့ရပါသည်။ ဤလေ့လာတွေ့ရှိချက်များ အရ Precast နည်းလမ်း၏ ပတ်ဝန်းကျင်ဆိုင်ရာ စွမ်းဆောင်ရည်သည် ဆောက်လုပ်ရေးပစ္စည်းများနှင့် စွမ်းအင်အသုံးပြုမှုများမှ အဓိကလွှမ်းမိုးမှုရှိကြောင်း သိရှိခဲ့ရပါသည်။ ထို့ကြောင့် Precast ဆောက်လုပ်ရေးစနစ်တွင် ကာဗွန်ထုတ်လွှတ်မှု နည်းသည့် ဆောက်လုပ်ရေးပစ္စည်းများကိုအသုံးပြုခြင်း၊ စက်ရုံ၏ စွမ်းအင်အကျိုးရှိထိရောက်မှုကိုတိုးမြှင့်ခြင်း၊ပြန်ပြည့်မြဲစွမ်းအင် စွမ်းအင်အသုံးပြုမှုမြှင့်တင်ခြင်းနှင့် သယ်ယူပို့ဆောင်ရေးတွင် ပို့ဆောင်ရေးစီမံမှုကိုပိုမိုကောင်းမွန်စေခြင်းတို့ကဲ့သို့သောနည်းလမ်းများကိုကျင့်သုံး ဆောင်ရွက်ရန်လိုအပ်ပါသည်။ ခြုံငုံသုံးသပ်ရမည်ဆိုပါက ရလဒ်များသည် ကာဗွန်ထုတ်လွှတ်မှု နည်းသော Precast ဆောက်လုပ်ရေးကို ပံ့ပိုးရန်နှင့် ထိုင်းနိုင်ငံနှင့် အခြားသော အလားတူ အခြေအနေရှိသည့် နိုင်ငံများအတွက် ရေရှည်တည်တံ့သော ဆောက်လုပ်ရေး အလေ့အကျင့်များ ကျင့်သုံးဆောင်ရွက်ရာတွင် လက်တွေ့ကျသော အသိအမြင်များကို ပေးနိုင်မည်ဖြစ်ပါသည်။

Carbon Footprints of Precast Construction: A Case Study of Two-Storey House in Thailand

1. Introduction

The escalating growth of the global population has fueled a surge in construction demand, anticipated to represent over 13.5% of Gross Domestic Product (GDP) by 2030, as reported by Oxford Economics (Robinson et al., 2021). Despite the economic benefits, the construction industry poses a significant environmental burden through excessive natural resource consumption, increased carbon dioxide (CO_2) emissions from energy use, and waste generation, leading to climate change, global warming, and resource depletion (Parry et al., 2007). Notably, the building sector contributes 40% to total energy consumption and 30% to annual greenhouse gas emissions, underscoring the urgent need to address emissions from material and energy use during construction (Onat & Kucukvar, 2020).

Traditionally, buildings are constructed on-site using conventional methods, where materials are transported from suppliers, and contractors oversee the construction process. Modern construction methods (MCMs) such as prefabrication and precast offer promising alternatives to conventional construction for enhancing the efficiency, economic viability, and reduce carbon emissions. MCMs such as prefabrication, precast, precast in-situ, and modular methods have gained popularity for their potential advantages regarding with environmental and economic aspects. Precast construction involves the off-site manufacturing and preassembly of building components before installation at the construction site (Goodier & Gibb, 2007). Many studies have analyzed the environmental performance of precast construction, utilizing quantitative methods to assess the environmental impacts.

In the context of Thailand, where the construction sector is rapidly expanding and facing increasing environmental challenges, it is essential to understand the potential impacts of different construction methods on CO_2 emissions. Although the precast construction method is widely used, there are currently no studies in Thailand that specifically examine CO_2 emissions from precast construction. Therefore, further research is needed to better understand the potential CO_2 emission impacts of precast construction.

To address this gap, this study aims to assess the carbon dioxide (CO_2) emissions associated with the precast construction method. A two-storey house project was used as a case study. The study focuses on the concrete structural system due to its predominant use in precast construction and its widespread application in residential buildings in Thailand. Through this investigation, the study seeks to provide meaningful insights into the environmental implications of precast construction, thereby supporting informed decision-making and contributing to sustainable construction practices in Thailand. Therefore, assessing CO_2 emissions from precast construction in Thailand is essential to quantify total emissions and identify the major emission sources associated with constructing a two-storey precast house.

2. Objectives

The research aimed to address the following objectives:

1) To assess carbon dioxide emissions of precast contruction
2) To identify the key emission sources contributing to carbon emissions in precast construction.

3. Materials and Methods

3.1 Description of the case building

This study used two-storey house project built with precast construction method to conduct the assessments of CO_2 emissions. The two-storey house project, located in Chonburi, Thailand, was constructed in 2023 by Concrete Products and Aggregate Co., Ltd (CPAC). CPAC is recognized for its commitment to green solutions and sustainable construction practices, aligning with its reputation as a leader in the construction industry for promoting environmentally friendly initiatives. The project information of case building is shown in Table 1.

Table 1. Profile of case building

Specifications	Case building
Types	Residential building
Location	Chonburi
Size (Cumulative Floor Area)	163m^2
Construction method	Precast
Foundations	Precast concrete pile foundation
Structure system	Concrete frame structure
Height	6.5m
Number of floors	2 floors
Structure frame: column, beam, exterior and interiors walls, slabs, staircase	Precast concrete

3.2 Research Methodology Framework

The research methodology framework consists of four key tasks aimed at fulfilling the research objective. Task 1 involves studying precast construction methods through literature review and direct observation of construction sites, guided by a conceptual framework. Task 2 focuses on data collection, including both primary and secondary data. Task 3 entails the assessment of carbon dioxide emissions by using mathematical calculations, followed by a comparative analysis between emission sources. Finally, Task 4 involves drawing conclusions and providing recommendations based on the study findings.

3.3 Scope of the Study

In this study, cradle-to-site life cycle stage was used as a scope for CO_2 emissions. Cradle to site encompasses all processes from extraction to transportation of the finished product to the construction site, including on-site assembly, construction, and waste disposal. Moreover, the process-based analysis was used as a quantitative method to analyze the CO_2 emission because it is a bottom-up method developed to assess the environmental impact of goods and services according to their production process, and it can be used to define and limit the sources and scope of CO_2 emissions calculation. Six key CO_2 emission sources were included in the system boundary of the CO_2 emission assessment, namely S1: construction materials, S2: construction materials transportation, S3: energy consumption at precast factory (off-site) and on-site, S4: precast components transportation, S5: Labour transportation, and S6: construction waste transportation. CO_2 emission per unit floor area of the case building house was selected as the functional unit in this study.

3.4 Quantitative method for CO2 emissions calculation

CO_2 emissions were calculated by multiplying the activity data and relevant emission factor of each activity or quantity. Total CO_2 emissions and emissions from six sources mentioned above were calculated as is equation 3-1.

$$TCE = \sum_{i=1}^{6} S_i \quad (3\text{-}1)$$

Where:

TCE = Total CO_2 emissions of six sources

S_i = ith CO_2 emission source during the construction process

CO_2 emissions from six sources within the study boundary were calculated by the following equations 3-2 to 3-7.

$$S1 = \sum_{m=0}^{m} Q_m \times e_m \quad (3\text{-}2)$$

Where:

S1	=	CO_2 emissions of all building materials ($kgCO_2$)
Q_m	=	Quantity of building material m (kg)
e_m	=	Carbon emission factor ($kgCO_2$/ kg)

$$S2 = \sum_{m=0}^{m} Q_m \times D_{mt} \times e_{mt} \quad (3\text{-}3)$$

Where:

S2	=	CO_2 emissions generated from transportation of buildings materials ($kgCO_2$)
Q_m	=	Quantity of building material m (tons)
D_{mt}	=	Distance between a distribution center and the off-site precast factory (km)
e_{mt}	=	Corresponding transportation (truck) related emission factor ($kgCO_2$/ton km)

$$S3 = \sum_{r=0}^{r} Q_r \times e_r \quad (3\text{-}4)$$

Where:

S3	=	CO_2 emissions from operation of construction and manufacturing equipment ($kgCO_2$)
Q_r	=	Energy consumption r of related requirements of construction techniques (kWh or L)
e_r	=	Emission factor of r consumption ($kgCO_2$/L or $kgCO_2$/kWh)

$$S4 = \sum_{p=0}^{p} Q_p \times D_{pt} \times e_{pt} \quad (3\text{-}5)$$

Where:

S4	=	CO_2 emissions of transportation of precast from the off-site precast factory to the project site ($kgCO_2$)
Q_p	=	Total amount of all precast components m (tons)
D_{pt}	=	Distance between the off-site precast factory and the project site (km)
e_{pt}	=	Corresponding transportation (truck) related emission factor ($kgCO_2$/ton km)

$$S5 = \sum_{m=0}^{m} W_L \times D_{Lt} \times e_{Lt} \quad (3\text{-}6)$$

Where:

S5	=	CO_2 emissions generated from transportation of labour ($kgCO_2$)
W_L	=	Weight of labour to be transported (tons)
D_{Lt}	=	Distance from the gathering point to off-site precast factory or construction site (km)
e_{Lt}	=	Corresponding transportation (truck) related emission factor ($kgCO_2$/ton km)

$$S6 = \sum_{m=0}^{m} Q_m \times D_{wmt} \times e_{mt} \quad (3\text{-}7)$$

Where:

S6	=	CO_2 emissions generated from transportation of waste ($kgCO_2$)
Q_m	=	Quantity of building material m (tons)
D_{mt}	=	Distance from the off-site precast factory to landfill (km)
e_{mt}	=	Corresponding transportation (truck) related emission factor ($kgCO_2$/ton km)

3.5. Data collection

The required data for precast house was obtained from the construction company by collecting the bill of quantities (BOQ) of building materials, architectural drawings, electricity bills and the energy consumption records of precast factory, transportation activities and waste related data. Moreover, field observations to precast factory was also done to know the real situation of how precast components were made, and discussions with experience engineers were also carried out during field observations. The data obtained from on-field observation, discussion with experience engineers from the construction company and BOQ were used for the calculation of CO_2 emissions. Round trip distances were utilized for accurate estimation of emissions associated with both outbound and return journeys.

The following information was collected for case building:

1. Basic information of the precast building which includes building type, location, number of floors, total floor area, frame type, floor-to-floor height.
2. List of building materials and the corresponding amount, waste factors, the locations of the distribution center of each building material and precast factory, location of labour gathering point, and types of vehicle used for transportation of building materials, labour and waste.
3. The energy consumption (electricity) for the precast components production at the manufacturing factory (off-site) and enegy used (diesel) for utilization of a mobile crane to lift precast components on-site.

This study primarily focuses on the structural elements of the building, particularly five precast components: precast walls, precast floors, precast beams, precast pile foundation, and precast staircase. The main building materials considered are cement, steel, sand, and aggregate. Waste factors during the production of precast components were estimated from construction company data and literature reviews. According to Loizou et al. (2021), the waste factor for concrete in precast production is between 0.5% and 3.5%, while Kwon et al. (2021) reported a waste range of 3% to 5% for steel. The data obtained from the precast factory were consistent with these ranges. As a result, average waste factors of 2% for concrete and 4% for steel were selected for this study. These values were then applied to the respective material quantities to determine the total waste generated. Energy consumption for precast construction was assessed for both off-site production and on-site installation. Off-site data were collected from electricity records of the precast plant, covering concrete preparation, reinforcement placement, and component casting, with machinery powered by electricity. On-site energy use focused on diesel consumption for a mobile crane during installation, while assembly was carried out manually.

The study required secondary data on emission factors to calculate carbon dioxide emissions associated with precast construction method. CO_2 emission factors can vary by region due to differences in manufacturing processes and material conditions. However, specific embodied CO_2 emission factors for building materials in Thailand were not readily available. To address this, emission factors for construction materials were sourced from reputable international institutions and reports, such as the Inventory of Carbon and Energy (ICE) and the Thailand Greenhouse Gas Management Organization (TGO). Additionally, emission factors for the energy used during both on-site and off-site construction activities, as well as fuel combustion for transportation, were obtained from the TGO.

4. Results

4.1. CO_2 emissions from building materials

The analysis of building materials in precast construction revealed significant differences in their contributions to embodied CO_2 emissions. Cement and steel are the main contributors, accounting for 47 percent and 50 percent of total emissions, respectively. Cement contributed 68.85 $kgCO_2$ per square meter, while steel, despite being used in smaller quantities, exhibited a higher emission intensity of 72.68 $kgCO_2$ per square meter. Sand and aggregate, although used in larger amounts, contributed much less to total emissions, with 1.18 $kgCO_2$ per square meter and 2.96 $kgCO_2$ per square meter, respectively, as shown in Figure 1.

In conclusion, the analysis underscored the significant contributions of cement and steel to CO_2 emissions in precast construction. Conversely, while sand and aggregate constituted larger quantities, their impact on CO_2 emissions in precast construction was relatively lower.

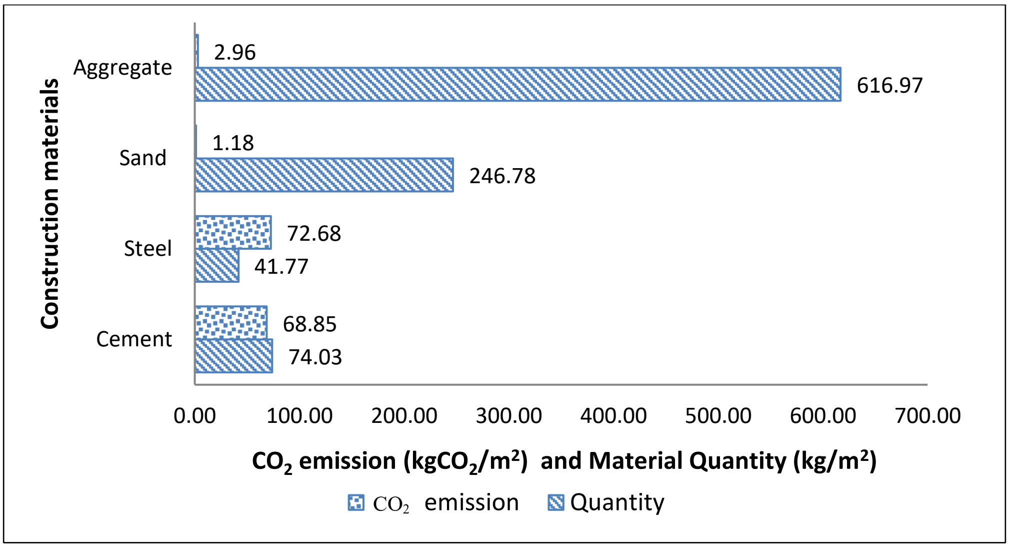

Figure 1: Quantities of building materials and associated CO_2 emissions

4.2. CO_2 emissions from transportation

The analysis of transportation-related CO_2 emissions in precast construction identified four main sources: building materials transport (S2), precast components transport (S4), labour transport (S5), and waste transport (S6). Building materials and precast components transport were the dominant sources, together accounting for 85 percent of total transportation emissions, with 3.61 $kgCO_2/m^2$ (45%) and 3.22 $kgCO_2/m^2$ (40%), respectively. These high emissions are driven by both the volume of materials and components and the distances they travel. Labour transport contributed 1.14 $kgCO_2/m^2$ (14%), reflecting the logistical demands of moving workers between gathering points, the precast factory, and the construction site. Waste transport had a minimal impact, producing only 0.09 $kgCO_2/m^2$ (1%), despite its importance in sustainable waste management. Figure 2 illustrates the CO_2 emissions from each transportation source.

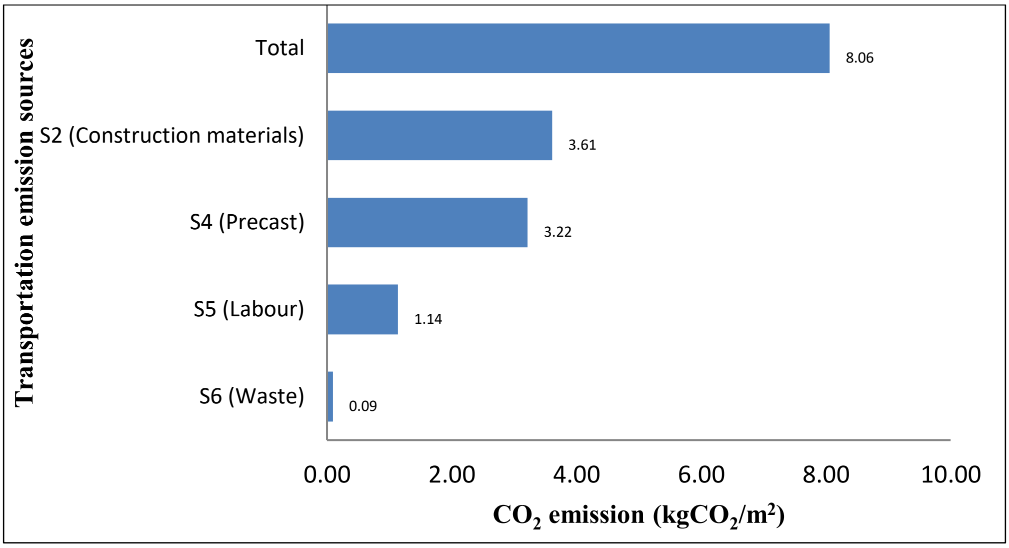

Figure 2 : CO_2 emissions from transportation emission sources

4.3. CO_2 emissions from off-site and on-site energy use

The analysis of energy-related CO_2 emissions reveals that off-site production at precast factories, mainly electricity used for concrete preparation, reinforcement placement, and component casting, contributed 12.16 $kgCO_2/m^2$, accounting for 56% of total energy emissions. On-site construction activities, dominated by diesel use for mobile cranes during component installation, contributed 9.69 $kgCO_2/m^2$ (44%). This indicates that off-site operations have a slightly higher environmental impact than on-site activities, largely due to the continuous and energy-intensive nature of factory processes. Figure 3 illustrates the CO_2 emissions associated with energy use in precast construction.

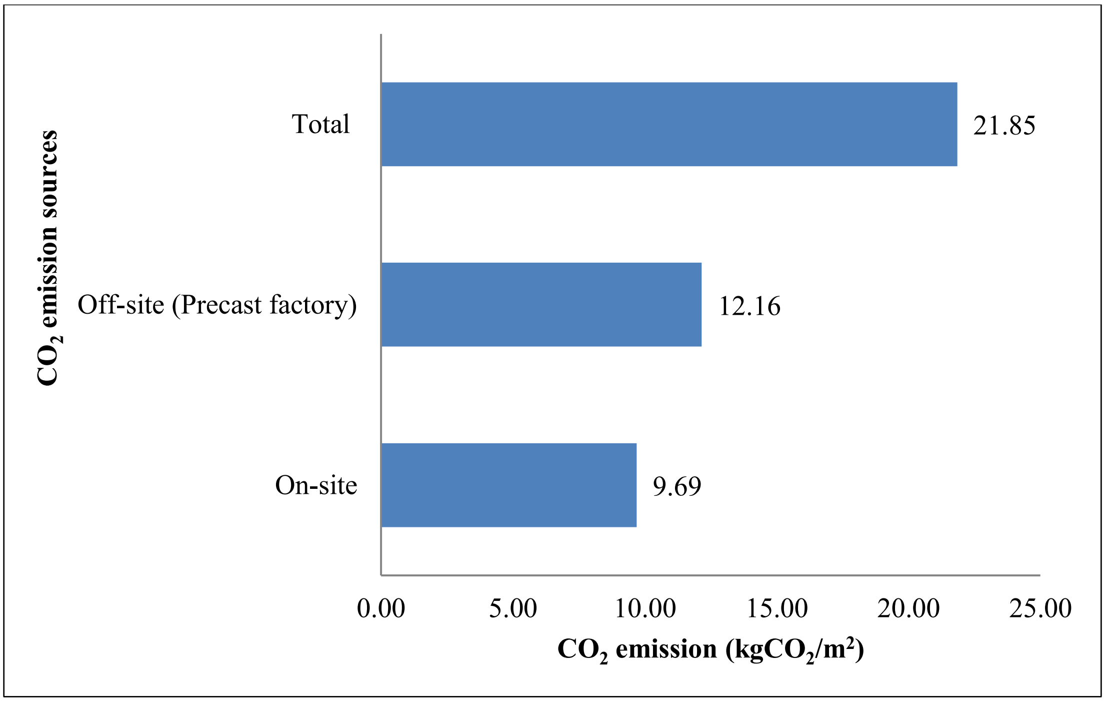

Figure 3: CO_2 emissions from off-site and on-site energy use

4.4. Total CO_2 emissions comparison

The total CO_2 emissions for Case A precast construction amounted to 175.58 $kgCO_2/m^2$. Among the emission sources, construction materials were the dominant contributor, accounting for 145.67 $kgCO_2/m^2$ or 83% of the total, reflecting the high carbon intensity of cement, steel reinforcement, and other structural components.

On-site and off-site energy consumption (S3) collectively accounted for approximately 12% of the total CO_2 emissions, equivalent to 21.85 $kgCO_2/m^2$. This contribution resulted from energy use during construction activities, including the operation of machinery and equipment in both the precast manufacturing facilities and the construction site. Electricity consumption in the precast factory was slightly higher than the diesel consumption used for lifting and installing precast elements on-site.

Transportation activities, including the movement of building materials, precast components, labour, and construction waste, represented the smallest share at 8.06 $kgCO_2/m^2$ (5%). Although lower than materials and energy, transport emissions remain a notable component of the overall carbon footprint. Figure 4 illustrates the distribution of CO_2 emissions from these sources, highlighting the significant impact of material selection and the relative contributions of energy and transportation in precast construction projects.

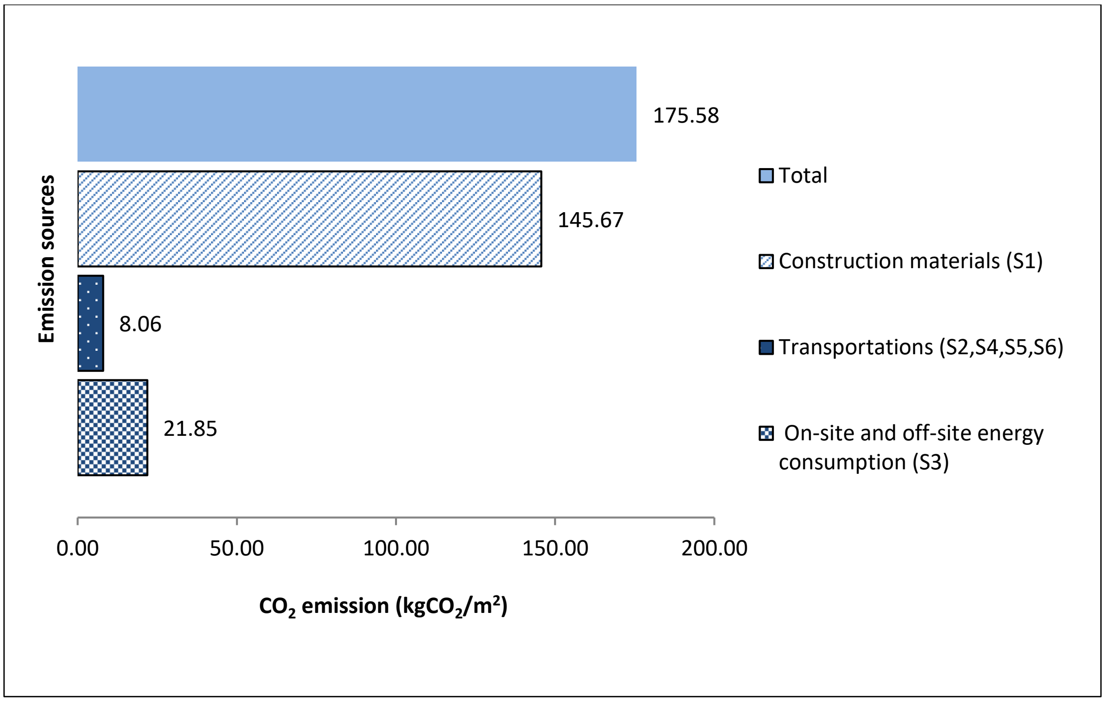

Figure 4: CO_2 emissions from various sources

5. Discussion

5.1. Interpretation of findings

The findings of this study demonstrate that the embodied carbon intensity of construction materials has a more significant influence on total emissions than material quantity alone. Cement and steel were identified as the dominant contributors to CO_2 emissions due to their highly energy-intensive manufacturing processes. Cement production releases substantial CO_2 through both fuel combustion and the calcination of limestone, while steel production involves high-temperature processing and chemical reduction, resulting in considerable greenhouse gas emissions. Conversely, sand and aggregates contributed relatively low emissions because they require minimal processing and energy input.

Transportation emissions were primarily driven by the transportation of building materials and precast components, reflecting both their quantities and transport distances. Although transportation contributed the smallest proportion of total emissions, reducing the carbon footprint associated with transport processes remains relevant for overall sustainability improvement. Strategies such as minimizing delivery distances, optimizing logistics, consolidating shipments, sourcing materials locally, and adopting low-emission vehicles can effectively reduce transportation-related CO_2 emissions in precast construction.

Energy use in precast construction also emerged as a notable emission contributor. Off-site factory operations, particularly electricity consumption during precast production, generated higher emissions than on-site construction activities. This highlights the importance of energy efficiency in manufacturing processes and the potential benefits of renewable electricity sources. Enhancing factory energy performance, improving machinery efficiency, and optimizing construction operations can significantly reduce emissions associated with energy use.

Overall, materials accounted for the largest share of total emissions, followed by energy consumption and transportation. This indicates that the environmental performance of precast construction is strongly influenced by material characteristics, manufacturing processes, and operational efficiency. The results emphasize the need to prioritize low-carbon material selection, improve production energy systems, and strengthen logistics management to advance sustainable precast construction.

5.2. Comparison with previous studies

The total CO_2 emission intensity of 175.58 $kgCO_2/m^2$ obtained in this study reflects emissions from construction materials, transportation activities, and both off-site and on-site energy use. Construction materials contributed 83 percent of the total emissions, supporting the widely reported finding that materials are the dominant source of emissions in precast systems. This result is in line with that of previous studies, which findings proved that emissions from construction materials are the highest among other emission sources (Du et al., 2019; Ji et al., 2018; Mao et al., 2013).

In comparison with international studies, the emission intensity observed in this Thai residential precast case is lower than values reported in Sri Lanka and China, where emission intensities of 258.86 $kgCO_2/m^2$ (Jayawardana et al., 2023) and 287.27 $kgCO_2/m^2$ (Ji et al., 2018) have been documented. The relatively lower emissions in this study may be attributed to factors such as shorter transportation distances, differences in construction practices, regional variations in energy mixes, and the use of emission factors that reflect local operational conditions.

Despite these comparatively favorable results, energy consumption remains a noteworthy contributor, reaffirming previous research that emphasizes the environmental significance of manufacturing energy in precast systems. This underscores the continued need for improving factory energy performance and adopting renewable energy solutions. While transportation emissions were comparatively low, consistent with findings from other studies, optimizing logistics still presents an opportunity for further emission reductions.

In summary, the results of this study are broadly aligned with international research indicating that construction materials are the primary drivers of CO_2 emissions in precast construction. However, regional conditions, energy systems, and logistics structures significantly influence the total emission intensity. Continued advancement in material innovation, improved factory energy systems, and strengthened sustainability practices remain essential to further enhance the environmental performance of precast construction.

6. Conclusion and recommendations

The assessment of CO_2 emissions for a two-storey precast residential building in Thailand indicates that total emissions amounted to 175.58 $kgCO_2/m^2$, with construction materials as the dominant contributor at 145.67 $kgCO_2/m^2$ (83%), followed by energy use at 21.85 $kgCO_2/m^2$ (12%), and transportation at 8.06 $kgCO_2/m^2$ (5%). Cement and steel are the primary sources of emissions due to their energy-intensive production, while energy use and transportation, though smaller contributors, are relevant targets for mitigation. These results highlight the critical role of material selection, energy performance, and process efficiency in influencing the carbon footprint of precast construction.

To reduce CO_2 emissions, several strategies are recommended. Material selection and optimization should focus on low-carbon alternatives such as recycled concrete, supplementary cementitious materials (SCMs), recycled steel, and locally sourced sustainable materials. Substitutes like bamboo or engineered timber, as well as reuse and recycling of materials, can further reduce emissions. Improving energy efficiency in precast factories, integrating renewable energy (solar, wind), enhancing machinery performance, and optimizing on-site operations are also essential to minimize environmental impact.

Transportation and logistics can be improved by minimizing transport distances, consolidating shipments, optimizing delivery schedules, and transitioning to low-emission vehicles where feasible. The adoption of advanced construction technologies such as Building Information Modeling (BIM) can enhance planning, material efficiency, and overall process management. Complementary measures include promoting research and development for sustainable construction, supporting policies that incentivize low-carbon practices, and investing in education and training to build industry capacity.

The implications of this study suggest that material selection, energy management, and operational strategies are key to reducing CO_2 emissions in precast construction. These findings provide actionable guidance for construction professionals, policymakers, and researchers to implement low-carbon practices and promote sustainable construction initiatives in Thailand. Implementing these strategies can support more sustainable building practices and contribute to global efforts toward low-carbon construction.

6.1. Limitations of the study

This study acknowledges key limitations that may affect the generalizability of its findings. The analysis was based on a single case study of a two-storey precast residential building in Thailand, which limits applicability to other building types and scales. Future research should include multiple precast projects across diverse building types and sizes to provide a more comprehensive understanding of CO_2 emissions in different contexts. Additionally, this study focused solely on cradle-to-site CO_2 emissions, excluding other life cycle stages such as building operation, maintenance, and end-of-life phases. Expanding future research to a full life cycle assessment and incorporating additional environmental impact categories, including operational energy use, water consumption, and resource depletion, would yield a more holistic evaluation of precast construction sustainability. Finally, the study relied on general international material and energy emission factors due to the limited availability of country-specific data for certain construction materials. Future studies should aim to use more precise, site-specific emission factors, consider emerging low-carbon materials, and investigate the long-term performance and durability of precast buildings to better assess environmental and sustainability outcomes.

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