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Carbon Footprint Analysis of Concrete Blocks in Thailand

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ABSTRACT

Concrete blocks are widely used for wall construction in Thailand, and reliable Carbon Footprint of Product (CFP) data for these blocks is essential for accurately estimating the embodied carbon of buildings—a crucial consideration in sustainable building design. This research evaluates the CFP of concrete blocks produced by a Thai factory, using a functional unit of one ton. The assessment applies a "Cradle to Gate" approach, covering both raw material acquisition and product manufacturing stages. The study period spans one year, from January 1, 2023, to December 31, 2023. Results show that the CFP for the case study block is 88.508 $kgCO_2eq/t$, with the raw material acquisition stage responsible for 84.778 $kgCO_2eq/t$ (95.79% of the CFP), and production stage emissions at 3.730 $kgCO_2eq/t$ (4.21% of the CFP). A detailed analysis of greenhouse gas (GHG) emissions reveals several key findings: (1) Portland cement is the primary source, accounting for 80.69% of the CFP; (2) emissions from the transportation of crushed stone and coarse sand are notably high; (3) electricity usage contributes 2.558 $kgCO_2eq/t$; and (4) broken concrete blocks constitute 12.93% of the mixture volume. This study not only addresses a critical gap in the availability of CFP data for concrete blocks in sustainable building analysis in Thailand, but also identifies key areas where GHG emissions associated with concrete block manufacturing can be reduced. The insights provided here are valuable for concrete block manufacturers across Thailand, especially those with similar production processes, as they work toward lowering the CFP of their products.

Keywords: Carbon Footprint of Product; Greenhouse Gas Emission; Concrete Block; Cradle to Gate; Sustainable Design

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1. Introduction

Sustainable building design aims to reduce environmental impacts throughout both construction and operation phases. Central to this approach is minimizing greenhouse gas (GHG) emissions, typically measured as carbon dioxide equivalents (CO_2e). GHG emissions from buildings generally fall into two categories: embodied carbon—which includes emissions from material production, transportation, construction, maintenance, and end-of-life disposal—and operational carbon, which results from energy used during building occupancy, such as heating, cooling, and lighting [1,2].

Globally, the building sector is responsible for approximately 39% of annual energy-related GHG emissions, with about 28% originating from operational carbon and 11% from embodied carbon [3]. Achieving truly sustainable buildings requires minimizing both embodied and operational carbon across the entire building lifecycle [4,5]. Access to reliable and context-specific emissions data is critical for informed decisions regarding material selection and building design.

A substantial body of international research has been devoted to assessing and analyzing embodied carbon to support sustainable building design. For instance, Diego Alvarez et al. [6] compared the embodied carbon of affordable housing in Indonesia, while Rudi Setiadji Agustiningtyas et al. [7] examined various types of affordable apartments in the same country. Rose Sadat Seyed Aboutorabi et al. [8] investigated how phase change materials and fly ash content affect the embodied carbon of a villa in Norway. Furthermore, Iddamalgoda Pathiranage Tharindu Sandaruwan et al. [9] in Sri Lanka, and M.K. Dixit and P. Pradeep Kumar [10] in the USA, explored differences in embodied carbon across building types and recommended emission reduction strategies. Likewise, Jingwen Liu and Chungyeon Won [11] examined the influence of façade typologies on embodied carbon in the retrofitting of university buildings in South Korea. Additionally, Shoma Kitayama et al. [12] calculated the embodied carbon of a case study school building in the United Kingdom, analyzed the share of GHG emissions attributable to lightweight exterior infill walls, and investigated potential emission reductions that could be achieved by demounting and reusing these walls.

In Thailand, Chalita Suwan and Thanutyot Somjai [13] evaluated and compared the embodied carbon of two single-family pilot houses: one constructed with conventional reinforced concrete and concrete block walls, and the other using interlocking blocks. Nantamol Limphitakphong et al. [14] assessed the embodied carbon of educational buildings and identified six primary materials as major contributors—or GHG hotspots—that require targeted mitigation strategies.

In contrast, some research has adopted a comprehensive approach by analyzing both embodied and operational carbon. For example, Makara Long et al. [15] evaluated total GHG emissions under different green building scenarios for Cambodian townhouses, while Badr Saad Alotaibi et al. [16] conducted a full lifecycle assessment (construction, operation, and demolition) for a high-rise residential building in India. Kaveh Samiei and Maurie Cohen [17] analyzed the effects of downsizing, urban densification, and material selection on lifecycle emissions in a residential building in New Jersey. Dinh-Linh Lea et al. [18] compared alternative design options to reduce both embodied and operational carbon in a Vietnamese office building.

In Romania, Tihamér Tibor Sebestyén [19] quantified emissions of carbon dioxide—a major GHG—associated with the manufacturing, construction, and operation phases of glamping structures to assess the net carbon dioxide impact of wood used in these buildings. In Spain, Javier García-López et al. [20] analyzed construction and operational GHG emissions to evaluate neighborhood renovation strategies for an obsolete residential housing estate. Samir Idrissi Kaitouni et al. [21] assessed GHG emissions during both the cradle-to-gate embodied phases (A1−A3) and the operational phase (B6) for a case study building, and compared the embodied carbon outcomes between conventional and eco-friendly construction materials. Yongkui Li et al. [22] evaluated both embodied and operational carbon for a case study hospital in Shanghai, China, to determine the GHG emission share from the production stage (A1−A3), construction stage (A4−A5), operation stage (B1−B7), and end-of-life stage (C1−C4), as well as to assess the influence of dynamic factors on the total GHG emissions.

In Thailand, researchers such as Nutvipa Rungreangthanaphol [23], Pipat Thaipradit [24], and Busakorn Duangkew [25] have investigated ways to reduce both embodied and operational carbon by modifying building envelope materials. Additionally, Nattaya Sangngamratsakul et al. [26] provided a comprehensive lifecycle emission profile for a detached house, highlighting variation in embodied emissions across different building materials.

Beyond buildings, several studies have focused on GHG emissions related to infrastructure. For example, Rafael Rodríguez et al.[27] calculated the carbon footprint of various elements during the TBM tunnel boring process at the design stage. D.R. Benoit[28] analyzed the potential for reducing embodied carbon in segmental lining and permanent spray concrete lining by adopting high-performance steel fiber reinforcement rather than rebar, in combination with optimized structural design and supplementary cementitious material (SCM) concrete mixtures. Jian Cao et al.[29] analyzed the GHG emissions of expressway bridges across six phases: design preparation, production processing, transportation, construction, operation, and disposal/recycling.

Accurate calculation of embodied carbon fundamentally depends on the availability of precise emission factor (EF) data. The most reliable EFs are those based on carbon footprint of product (CFP) disclosures from product manufacturers, as these figures directly reflect actual production processes and compliance with relevant regulations. In the absence of such data, researchers often turn to international databases or rely on estimated EFs derived from assumed material compositions and supply chains, which can introduce significant uncertainties. Even for ostensibly similar materials, GHG emissions can vary considerably depending on raw material sources, manufacturing practices, and transport distances. Consequently, reliance on generic or foreign EF values may undermine the effectiveness of GHG reduction strategies within the local context.

In Thailand, there is a significant lack of CFP data for construction materials, which limits the reliability of embodied carbon assessments across the built environment. The availability of CFP data for construction materials would greatly enhance the credibility of embodied carbon analyses and enable more effective strategies for advancing sustainable construction practices in Thailand's industry. Concrete blocks, for example, are widely used for walls and fences due to their size, ease of installation, low labor costs, and affordability. Nonetheless, most studies evaluating the embodied carbon of Thai buildings continue to rely on EF values for concrete blocks from international databases[23–25], due to the current lack of locally sourced CFP data. This highlights the urgent need for local CFP data for concrete blocks in Thailand.

This study aims to address this gap by evaluating the CFP of concrete blocks manufactured in Thailand. By providing localized data, the accuracy of embodied carbon assessments can be significantly improved, thus supporting better material selection and more sustainable building design in the Thai context. Furthermore, the findings will help local concrete block manufacturers identify key emission sources and develop targeted strategies for cleaner production. This research builds upon and extends our previous work presented at the 29th National Convention on Civil Engineering, organized by the Engineering Institute of Thailand[30].

2. GHG Emissions of Concrete Blocks

A review of the literature reveals a wide range of GHG emission values for concrete blocks reported in various databases and research studies. Key findings from notable sources are summarized below:

The Inventory of Carbon and Energy (ICE), compiled by Hammond et al.[31], reports GHG emissions for concrete blocks based on a functional unit of 1 kg, with categories defined by compressive strength—8 MPa, 10 MPa, 12 MPa, and 13 MPa—corresponding to emissions of 0.063, 0.078, 0.088, and 0.107 kgCO_2eq/kg, respectively.

Liu, Hossain, and Ling[32] investigated the carbon footprint of blocks produced using natural aggregates, reporting a GHG emission of 97.00 kgCO_2eq per metric ton. Dahmen, Kim, and Ouellet-Plamondon[33], in a life cycle assessment of masonry blocks, found that a standard product block (390 mm × 190 mm × 190 mm, 14.93 kg) emitted 1.76 kgCO_2eq per piece, or 117.83 kgCO_2eq/t. Surgelas and Surgelas[34], using a functional unit of 1 m² of product (weighing 155.86 kg/m²), calculated emissions at 12.00 kgCO_2/m², equivalent to 76.99 kgCO_2eq/t.

Kornboonraksa and Srisukphun[35] examined the environmental impacts of incorporating fly ash in concrete blocks and reported GHG emissions of 19.55 kgCO_2eq/m² (weighing 131.58 kg/m²), equivalent to 148.59 kgCO_2eq/t. Zengfeng et al.[36], studying blocks with recycled and natural aggregates, found that traditional blocks using natural aggregates emitted 109.00 kgCO_2eq/m³ (weighing 2,166.99 kg/m³), or 50.30 kgCO_2eq/t. Liu et al.[37] reported that concrete blocks with natural aggregates emitted 323.84

$kgCO_2eq/m^3$ (weighing 2,435 kg/m^3), or 132.99 $kgCO_2eq/t$.

Khizra Kulsoom et al.[38] quantified product stage (modules A1–A3) carbon emission for concrete blocks produced in Pakistan using industrial data. Their site-based data collection covered variables such as cement, sand, and crushed stone per block, as well as transport distances and fuel consumption. They reported an GHG emission of 0.082 $kgCO_2eq/kg$, or 82.00 $kgCO_2eq/t$.

It should be noted that the majority of studies estimated GHG emissions using standard material quantities and typical operational procedures, including plant activities and transportation to the factory gate. Only a handful of studies, such as that by Kulsoom et al.[38], have incorporated industry-sourced data. However, even in these cases, it remains unclear whether the key data used for the calculations truly constitute primary data, as well as whether these data were collected systematically and over an appropriate period of time.

Furthermore, the reviewed literature reveals significant variation in reported GHG emission values for concrete blocks, ranging from 50.30 $kgCO_2eq/t$ to 148.59 $kgCO_2eq/t$. This variation likely arises from differences in regional product standards, raw material sources, emission factors of constituent materials, production technologies, and methodological assumptions specific to each study. These inconsistencies underscore the necessity for region-specific, product-level CFP assessments based on accurate, primary industrial data. Such efforts are critical to reducing uncertainties in embodied carbon calculations for buildings utilizing concrete blocks and to support more reliable, sustainable material selection in construction.

3. Types of Concrete Blocks in Thailand and Case Study Scope

Concrete block products in Thailand are primarily classified into two types, based on their intended structural use and regulated by the Thai Industrial Standards. The first type is hollow load-bearing concrete masonry units, governed by TIS 57−2560, which specifies four main quality criteria: an average compressive strength of at least 140 ksc for three tested blocks, dimensional tolerance within 2 millimeters, a minimum wall thickness of 12 millimeters, and, for moisture-controlled blocks, a regulated maximum water absorption rate. The second type is hollow nonloadbearing concrete masonry units, regulated by TIS 58−2560. These blocks must have an average compressive strength of at least 25 ksc and a dimensional tolerance within 2 millimeters.

This study focuses on the latter category—hollow non-loadbearing concrete blocks. The case study product is a 19 × 39 × 7 cm concrete block that meets the requirements of TIS 58-2560, with a specified minimum compressive strength of 25 ksc (2.451 MPa). The product analyzed is manufactured by the 302nd Engineer Regiment, 3rd Engineer Brigade's concrete block production unit, located in Somdet Phra Borom Trailokkanat Camp, Mueang District, Phitsanulok Province. The factory specializes in the production of only one block type and size, using a manually operated molding machine and a workforce of 10 people. Its maximum daily production capacity is 1,200 blocks. In 2023, a total of 185,791 blocks were produced, weighing 1,170.48 tons in total, with an average block weight of 6.30 kg per unit.

The scope of the CFP assessment in this study adopts a "Cradle to Gate" approach, which covers two main stages of the product's lifecycle: the raw material acquisition stage and the product production stage. The raw material acquisition stage includes raw material production and transportation, while the product production stage comprises production operations, waste transportation, and waste disposal. The functional unit for the analysis is one ton of 19 × 39 × 7 cm concrete blocks, with the assessment period spanning from January 1 to December 31, 2023.

4. Research Methodology

To achieve the objectives of this research, the study was conducted in five main steps:

1) Study of the Production Process. This step involved a detailed examination of the production process for the case study concrete block. The objective was to identify the various production steps, the resources used, and the output product and waste at each stage, as well as the associated activities and data sources.

2) Collection of Production Process Data. Data from each step of the production process were collected to compile a comprehensive life cycle analysis (LCA) for the concrete block product. The gathered data included the types, quantities, and units of input resources, output products, and pro-

cess waste for each production step, along with the associated activities. This information was essential for assessing the GHG emissions during both the raw material acquisition and product production stages. The input resources and output products were organized according to the mass balance of the process, ensuring that all resource flows—such as raw materials, energy inputs, production outputs, and process waste—were accurately recorded, reflecting the resource usage and emissions throughout the production system.

3) Collection of GHG emission factors (EFs). In this step, EFs for each resource or activity were gathered from various sources. Special attention was paid to ensuring the data was current and reliable.

4) Calculation of GHG emissions. GHG emissions for each production step were calculated by applying the relevant EFs to the resource or activity data, as outlined in Equation (1).

$$\text{GHG Emission}_i = Q_i \times EF_i \quad (1)$$

Where: i—a particular resource or activity.

GHG Emission_i—the amount of GHG emissions associated with the resource or activity i, $kgCO_2eq$.

Q_i—the quantity of the resource or activity i, unit; such as kg, liters, kWh, tkm, or km.

EF_i—the emission factor per unit of the resource or activity i, $kgCO_2eq$ per unit.

5) Determination of the CFP and Analysis of the Results. In this step, the data from step 4 were summarized to calculate the CFP of the case study concrete block. The CFP is calculated using Equation (2).

$$CFP = \sum \text{GHG Emission}_i \quad (2)$$

Where: i—a particular resource or activity.

CFP—the product's carbon footprint, reported in three significant digits, $kgCO_2eq$.

GHG Emission_i—the amount of GHG emissions associated with the resource or activity i, $kgCO_2eq$.

The GHG emission data were also analyzed and presented in two forms: 1) GHG emissions from each production step across the life cycle, and 2) GHG emissions related to specific raw materials or waste throughout the life cycle. This approach helps to understand the environmental impact at different steps of the production process and highlights the contributions of various raw materials and waste management activities to the total emissions.

5. Production Process

From the study of the production process of the concrete block case study, it was found that the production process can be divided into five steps: 1) inspecting and preparing raw materials, 2) mixing the raw materials, 3) conveying the mixture to the molding station, 4) molding the concrete block, and 5) naturally curing the concrete block. The list and quantities of input resources, output products, and process waste for each step are shown in **Figure 1**.

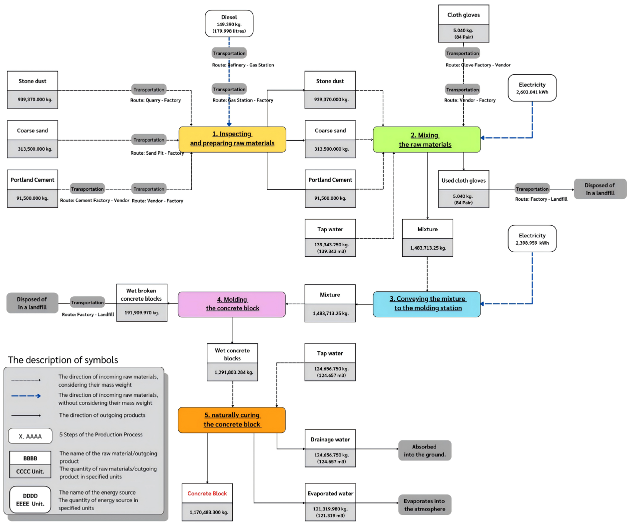

Figure 1. Inputs and outputs at each step of the concrete block production process.

Detailed information regarding the sources of data for input resources, output products, and process waste at each production step is presented in **Table A1** of the Appendix. In addition, data on the transportation of raw materials and production waste, obtained from surveys—including the types of transport vehicles, transportation distances, number of trips, and payload weights—are also provided in **Table A2** of the **Appendix A**.

6. GHG Emissions Calculation

To estimate GHG emissions from each source, emission factors (EFs) related to raw material production, fuel combustion, electricity generation, and waste disposal—which are essential for determining the CFP of concrete blocks—were compiled. These data are provided in **Table A3** of the Appendix. In addition, emission factors for various transportation activities were also gathered and are summarized in **Table A4** of the Appendix.

GHG emissions attributable to each emission source at every production step, both during the raw material acquisition stage and the product manufacturing stage, were calculated by utilizing the quantities of resources and transportation activities presented in **Figure 1** and **Tables A1** and **A2**, together with the emission factors shown in **Tables A3** and **A4**, following the approach described in Equation (1). Since this study assessed the CFP of concrete blocks per functional unit (FU), defined as one ton of product, the resource consumptions recorded in 2023 were normalized to a per-FU basis by dividing the total quantities by the annual production volume of 1,170.4833 tons in 2023.

Detailed calculations of GHG emissions associated with raw material production and transportation during the raw material acquisition stage are provided in **Table A5** of the **Appendix A**. **Table A6** of the **Appendix A** presents emissions from fuel combustion and electricity consumption at each production step, illustrating the direct contribution of energy inputs to the total emissions. **Table A7** of the **Appendix A** outlines emissions resulting from the transportation and disposal of production waste, highlighting waste management-related emissions across the production process.

The emission factors for the transportation of raw materials and production waste per kilogram, as detailed in **Tables A5** and **A7**, were calculated as follows: total emissions from the transportation of raw materials and production waste were first determined by considering the transportation distance, number of trips, and the relevant emission factors for each transportation activity. The resulting total emissions were then divided by the total weight of the transported materials to yield per-kilogram emission factors.

The calculated results for GHG emissions associated with each emission source at every production step, during both the raw material acquisition and product manufacturing stages, are summarized in **Table 1**.

Table 1. GHG emissions.

Item	Unit	Quantity Per FU	Life Cycle Stage / Emission ($kgCO_2eq$): Raw Material Acquisition Stage – Material Production	Raw Material Acquisition Stage – Material Transportation	Production Operations Stage – Production Operations	Production Operations Stage – Waste Transportation	Production Operations Stage – Waste Disposal
Inspecting and Preparing Raw Materials							
Stone Dust	kg	802.549	2.488	8.025	-	-	-
Coarse Sand	kg	267.838	1.232	1.420	-	-	-
Portland Cement	kg	78.173	68.949	2.470	-	-	-
Diesel	kg	0.128	0.030	0.020	0.459	-	-
Total			72.699	11.935	0.459	-	-
Mixing the Raw Materials							
Cloth gloves	kg	0.004	0.008	0.014	-	0.000	0.008
Tap water	m^3	0.119	0.064	-	-	-	-
Electricity	kWh	2.224	-	-	1.331	-	-
Total			0.072	0.014	1.331	0.000	0.008
Conveying the Mixture to the Molding Station							
Electricity	kWh	2.050	-	-	1.227	-	-
Total			-	-	1.227	-	-
Molding the Concrete Block							
Broken concrete blocks	kg	163.958	-	-	-	0.705	0.000
Total			-	-	-	0.705	0.000
Naturally Curing the Concrete Block							
Tap water	m^3	0.107	0.058	-	-	-	-
Total			0.058	-	-	-	-
Total GHG Emissions for All 5 Steps of the Production Process			72.829	11.949	3.017	0.705	0.008

As shown in **Table 1**, although emissions directly associated with broken concrete blocks are relatively low at 0.705 $kgCO_2eq/t$, the amount of waste generated is substantial—163.958 kg/t, or 12.93% of the total admixture (1,267.560 kg/t), which is composed of stone dust (802.549 kg/t), coarse sand (267.838 kg/t), Portland cement (78.173 kg/t), and tap water (119.000 kg/t).

7. Findings and Discussion

CFP of Concrete Block Product

The consolidated GHG emission data from all production stages (presented in **Table 1**) are summarized in **Table 2.** Calculations based on Equation 2 indicate that the CFP of concrete block production is 88.508 $kgCO_2eq/t$, a value that falls within the range reported in previous studies (50.300–148.590 $kgCO_2eq/t$)[11–17].

Table 2. GHG emissions by production step.

No.	Production Steps	Life Cycle Stage / GHG Emissions ($kgCO_2eq$)					
		Raw Material Acquisition Stage		Product Production Stage			Total Emissions
		Material Production	Material Transportation	Production Operations	Waste Transportation	Waste Disposal	
1	Inspecting and preparing raw materials	72.699	11.935	0.459	-	-	85.093
2	Mixing the raw materials	0.072	0.014	1.331	0.000	0.008	1.425
3	Conveying the mixture to the molding station	-	-	1.227	-	-	1.227
4	Molding the concrete block	-	-	-	0.705	0.000	0.705
5	Naturally curing the concrete block	0.058	-	-	-	-	0.058
Total		72.829	11.949	3.017	0.705	0.008	88.508
			84.778			3.730	
Percentage of Emissions			**95.79%**			**4.21%**	**100.00%**

Key Sources of GHG Emissions

Data analysis presented in **Table 2** clearly demonstrates that the raw material acquisition stage is the predominant contributor to total GHG emissions, accounting for 95.79% of the CFP, while the production stage contributes only 4.21%. Notably, the inspection and preparation of raw materials constitute the largest single emission source, representing 96.14% of the CFP (85.093 $kgCO_2eq/t$).

A comparative analysis between the present study—using a cement-to-aggregate ratio of 1:13.69—and the work of Kornboonraksa and Srisukphun[35], who employed a higher ratio of 1:5, reveals a marked difference in results. Kornboonraksa and Srisukphun reported a CFP of 148.590 $kgCO_2eq/t$, which is 67.88% higher than that found in this study. This substantial difference underscores the strong influence of mix design and cement content on CFP outcomes. Optimizing mix proportions, particularly by reducing the cement content, can therefore play a pivotal role in lowering GHG emissions associated with concrete block manufacturing.

A further comparison with Khizra Kulsoom et al.[38] from Pakistan, which utilized a cement-to-aggregate ratio of 1:12, yielded a CFP value of 82.000 $kgCO_2eq/t$—just 7.35% lower than in this study. When emissions from waste transport and disposal are excluded for an apples-to-apples comparison, the difference narrows further to 2.795 $kgCO_2eq/t$ (3.27%). At the stage level, GHG emissions from raw material production in this study were slightly lower than those reported by Kulsoom et al. (72.829 vs. 78.000 $kgCO_2eq/t$), likely attributable to the lower cement content in the mix. However, emissions from raw material transport and manufacturing stages in this study are higher, possibly due to factors such as longer transport distances, differences in production technologies, or varying energy sources.

Emissions Attribution by Material and Waste Type

Further breakdowns (**Table 3**) show that, next to Portland cement, stone dust, coarse sand, and electricity are the most significant contributors. Portland cement production and transportation identified as the principal emission source (71.419 kgCO_2eq/t or 80.69% of CFP). Transportation emissions for aggregates such as stone dust and sand also emerge as significant, surpassing the emissions generated during their production phase. Although emissions from production waste management are relatively low as a percentage of total emissions, effective management can have a disproportionate positive effect on both emission reduction and material efficiency.

Table 3. GHG emissions by material type and product waste.

No.	Type of Raw Material or Waste	Life Cycle Stage / GHG Emissions (kgCO_2eq)					
		Raw Material Acquisition Stage		Product Production Stage			Total Emissions
		Material Production	Material Transportation	Production Operations	Waste Transportation	Waste Disposal	
1	Stone Dust	2.488	8.025	-	-	-	10.513
2	Coarse Sand	1.232	1.420	-	-	-	2.652
3	Portland Cement	68.949	2.470	-	-	-	71.419
4	Tap water	0.122	-	-	-	-	0.122
5	Cloth gloves	0.008	0.014	-	0.000	0.008	0.030
6	Diesel	0.030	0.020	0.459	-	-	0.509
7	Electricity	-	-	2.558	-	-	2.558
8	Broken concrete blocks	-	-	-	0.705	0.000	0.705
Total		72.829	11.949	3.017	0.705	0.008	88.508
			84.778			3.730	
Percentage of Emissions			95.79%			4.21%	100.00%

Implications for Practice

The findings point to several actionable strategies for reducing the CFP of concrete block production:

Substitute Portland Cement: Given that Portland cement is the predominant emission source, replacing it with lower-carbon alternatives such as hydraulic cement—which has a lower emission factor (0.824 kgCO_2eq/kg compared to 0.882 kgCO_2eq/kg for Portland cement)—can meaningfully reduce the CFP by approximately 5.31%.

Optimize Aggregate Sourcing: Since transportation of aggregates is a major contributor to emissions, sourcing these materials from closer suppliers can have an immediate impact. For example, reducing the transport distance by 10 km for stone dust and sand can lower the carbon footprint by 0.70% and 0.25%, respectively, while also reducing costs.

Enhance Waste Management: Production waste management—particularly with respect to broken concrete blocks, which account for as much as 12.93% of the total admixture—warrants significant attention. Implementing stricter quality control measures and optimizing manufacturing processes can substantially mitigate not only the emissions associated with the transportation and disposal of production waste, but also reduce the demand for raw materials and the resulting environmental impacts. These improvements have the potential to increase production yield by 14.86% and decrease GHG emissions by up to 13.63%.

Use Cleaner Energy Sources and Improve Equipment Efficiency: Although emissions from electricity and diesel usage are relatively smaller, they can be further reduced by adopting cleaner energy sources and improving equipment efficiency. For example, switching to cleaner energy and enhancing the energy performance of production equipment could decrease GHG emissions from electricity use by up to 2.89%.

Implement Resource Management Practices: Practices such as water reuse during concrete curing offer additional environmental benefits by conserving resources and minimizing waste.

These results provide industry practitioners and policymakers with a clear foundation for prioritizing emission reduction efforts. Beginning with substituting Portland cement, focusing on local aggregate sourcing, enhancing waste management, using cleaner energy sources and improving equipment efficiency, and implementing resource management practices, the identified strategies offer a comprehensive, stepwise approach to decarbonizing concrete block manufacturing. Such measures not only reduce environmental impacts but can also improve operational efficiency and lower production costs.

Collectively, these recommendations offer a practical roadmap for reducing the CFP of concrete block production and aligning with broader sustainability goals for the construction sector.

8. Conclusion and Limitations

This study determined that the CFP of concrete blocks produced in Thailand, as calculated using a Cradle-to-Gate approach, is 88.508 $kgCO_2eq/t$. This figure provides a valuable reference for both the academic community and the Thai Architecture, Engineering, and Construction (AEC) industry in evaluating embodied carbon in construction materials. The analysis revealed that emissions from the manufacturing stage account for only 3.730 $kgCO_2eq/t$ (4.21% of the CFP), while emissions from raw material acquisition are substantially higher at 84.778 $kgCO_2eq/t$ (95.79% of the CFP). These results indicate that efforts to reduce emissions during the manufacturing process, which is directly controlled by factories, will have limited impact. Instead, greater reductions can be achieved by prioritizing the selection of lower-carbon raw materials.

A detailed assessment of emission sources showed that Portland cement is the largest contributor, responsible for 80.69% of the CFP. Crushed stone and coarse sand significantly contribute to transportation-related emissions, electricity consumption adds 2.558 $kgCO_2eq$ per ton, and broken concrete blocks comprise 12.93% of the mix by volume. These insights reveal critical intervention points where concrete block manufacturers—especially in Thailand and similar settings—can implement effective carbon reduction strategies.

Despite the rigorous and systematic approach taken in this research, several limitations may introduce minor uncertainties to the reported CFP values. Quantities for certain raw materials, like stone dust and coarse sand, were based on invoice data rather than direct measurement, which may cause slight inaccuracies. Transportation distances were estimated by the shortest routes via Google Maps, which may not correspond precisely to actual routes taken, potentially leading to small discrepancies in GHG emission calculations. Some emission factors were sourced from reputable secondary data due to limited primary data from manufacturers, possibly introducing minimal inaccuracies; however, these are generally considered acceptable in academic studies. For fuel combustion, standardized emission factors from the Thailand Greenhouse Gas Management Organization were used in the absence of direct measurements, with any resulting differences expected to be minor. Furthermore, the total weight of finished concrete blocks was estimated from production volumes and average block weights, while the weights of wet and broken blocks were approximated using mass conservation principles. These methods introduce additional, albeit minor, uncertainties.

Overall, these limitations are deemed acceptable and do not significantly affect the principal findings of the study. However, they should be considered when interpreting and applying these results in future research or practical implementations.

Author Contributions

Conceptualization, N.S. and A.S.; methodology, N.S. and A.S.; data curation, N.S. and A.S.; formal analysis, N.S., T.S., S.K., A.B., and A.S.; writing—original draft preparation, N.S. and A.S.; writing—review and editing, T.S., S.K., A.B., and A.S. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data will be made available by the authors upon request.

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Conflicts of Interest

The authors declare that there are no conflict of interest.

Appendix A

Table A1. Sources of data for input resources, output products, and process waste.

Input Resources, Output products, and Process Waste		Source of Data
1.	Stone dust	Vendor invoice
2.	Coarse sand	Vendor invoice
3.	Portland Cement	Vendor invoice
4.	Cloth gloves	Vendor invoice
5.	Tap water	Water utility records
6.	Electricity	Electricity utility records and allocation
7.	Diesel	Calculated based on machine operating hours
8.	Mixture	Calculated from the total input materials in Step 2, which include stone dust, coarse sand, cement, and water.
9.	Concrete blocks	Calculated from the number of products produced in 2023
10.	Evaporated water	Allocated from the total water used in Step 2
11.	Wet concrete blocks	Calculated from the total output materials in Step 5, which include evaporated water and the concrete blocks.
12.	Wet broken concrete blocks	Calculated from the difference between the input materials in Step 4, which are the mixture, and the output of this step, which consists of the wet concrete blocks.

Table A2. Data on transporting raw materials and production waste.

No.	Raw Material/Transport Vehicle	Data	To Destination Trip (% Load)				Return Trip
			100%	75%	50%	0%	0%
1	Stone dust (Total Weight: 939,370.00 kg)						
1.1	Vehicle: 18-Wheeler Semi-Trailer Maximum Payload Capacity: 32 tons Distance: 129.00 km/trip Route: Quarry - Factory	Number of Trips:	32.0000				32.0000
		Payload: (kg)	29,355.31				-
2	Coarse sand (Total Weight: 313,500.00 kg)						
2.1	Total Weight: 313,500.00 kg Vehicle: 18-Wheeler Semi-Trailer Maximum Payload Capacity: 32 tons Distance: 65.40 km/trip Route: Sand Pit - Factory	Number of Trips:	11.0000				11.0000
		Payload: (kg)	28,500.00				-
3	Portland Cement (Total Weight: 91,500 kg)						
3.1	Vehicle 1: Small 4-Wheeled Pickup Truck Maximum Payload Capacity: 7 tons Distance: 26.80 km/trip Route: Vendor – Factory	Number of Trips:	1.0000	14.0000	10.0000		25.0000
		Payload: (kg)	6,500.00	5,000.00	1,500.00		-

Table A2. *Cont.*

No.	Raw Material/Transport Vehicle	Data	To Destination Trip (% Load)				Return Trip
			100%	75%	50%	0%	0%
3.2	Vehicle 2: 18-Wheeler Closed-Box Semi-Trailer Maximum Payload Capacity: 32 tons Distance: 314.00 km/trip Route: Portland Cement Factory – Vendor	Number of Trips:	2.8594				2.8594
		Payload: (kg)	32,000.00				-
4	Diesel (Total Weight: 149.39 kg)						
4.1	Vehicle 1: Small 4-Wheeled Pickup Truck Maximum Payload Capacity: 7 tons Distance: 25.40 km/trip Route: Gas Station - Factory	Number of Trips:				1.0000	1.0000
		Payload: (kg)				149.39	-
4.2	Vehicle 2: 18-Wheeler Semi-Trailer Maximum Payload Capacity: 32 tons Distance: 700.00 km/trip Route: Refinery - Gas Station	Number of Trips:	0.0047				0.0047
		Payload: (kg)	32,000.00				-
5	Cloth gloves (Total Weight: 5.04 kg)						
5.1	Vehicle 1: Small 4-Wheeled Pickup Truck Maximum Payload Capacity: 7 tons Distance: 26.80 km/trip Route: Vendor – Factory	Number of Trips:				1.0000	1.0000
		Payload: (kg)				5.04	-
5.2	Vehicle 2: 18-Wheeler Semi-Trailer Maximum Payload Capacity: 32 tons Distance: 700 km/trip Route: Glove Factory - Vendor	Number of Trips:	0.0002				0.0002
		Payload: (kg)	32,000.00				-
6	Used cloth gloves (Total Weight: 5.04 kg)						
6.1	Vehicle: 6-Wheeled Garbage Truck Maximum Payload Capacity: 11 tons Distance: 40 km/trip Route: Factory – Landfill	Number of Trips:	0.0005				0.0005
		Payload: (kg)	11,000.00				-
7	Broken Concrete Blocks (Total Weight: 191,909.97 kg)						
7.1	Vehicle: Large 6-Wheeled Pickup Truck Maximum Payload Capacity: 11 tons Distance: 40 km/trip Route: Factory – Landfill	Number of Trips:	18.0000				18.0000
		Payload: (kg)	10,661.67				-

Table A3. EFs associated with raw material production, fuel combustion, electricity generation, and waste disposal.

No.	Item	Unit	Life Cycle Stage	EF ($kgCO_2eq$/unit)	Reference
1	Coarse sand	kg	Raw material production	0.0046	Sukontasukkul, P. [39]
2	Stone dust	kg	Raw material production	0.0031	Kittipongvises, S. [40]
3	Portland cement	kg	Raw material production	0.8820	Concrete Products and Aggregate Company Limited [41]
4	Tap water	m^3	Raw material production	0.5410	Thailand Greenhouse Gas Management Organization [42]
5	Cloth gloves	kg	Raw material production	2.1100	Thailand Greenhouse Gas Management Organization [42]
6	Diesel oil	kg	Raw material production	0.2370	Bangchak Corporation Public Company Limited [43]
7	Diesel oil	L	Production operations (combustion)	2.9793	Thailand Greenhouse Gas Management Organization [44]
8	Electricity	kWh	Production operations (generation)	0.5986	Thailand Greenhouse Gas Management Organization [42]
9	Landfilling textile waste	kg	Waste disposal	2.0000	Thailand Greenhouse Gas Management Organization [45]

Table A4. Data on transporting raw materials and production waste.

No.	Vehicle Description	Unit	EF* ($kgCO_2eq$/unit)
1	18-Wheeler Semi-Trailer, Maximum payload capacity: 32 tons, normal operation		
	- 100% Loading	tkm	0.0443
	- 0% Loading	km	0.8684
2	18-Wheeler Closed-Box Semi-Trailer, Maximum payload capacity: 32 tons, normal operation		
	- 100% Loading	km	0.0449
	- 0% Loading	km	0.8215
3	Small 4-Wheeled Pickup Truck, Maximum payload capacity: 7 tons, normal operation		
	- 100% Loading	tkm	0.1411
	- 75% Loading	tkm	0.1840
	- 50% Loading	tkm	0.2698
	- 0% Loading	km	0.3131
4	6-Wheeled Garbage Truck, Maximum payload capacity: 11 tons, normal operation		
	- 100% Loading	tkm	0.0475
	- 0% Loading	km	0.4923
5	Large 6-Wheeled Pickup Truck, Maximum payload capacity: 11 tons, normal operation		
	- 100% Loading	tkm	0.0613
	- 0% Loading	km	0.4923

*Source: Thailand Greenhouse Gas Management Organization [42].

Table A5. Data on transporting raw materials and production waste.

Item	Resource Amount			Raw Material Acquisition Stage			
				Raw material Production Substage		Raw material Transportation Substage	
	Unit	Quantity (2023)	Quantity per FU	Emission Factor ($kgCO_2eq$/unit)	Emission ($kgCO_2eq$)	Emission Factor ($kgCO_2eq$/unit)	Emission ($kgCO_2eq$)
Inspecting and Preparing Raw Materials							
Stone Dust	kg	939,370.00	802.549	0.0031	2.488	0.0100	8.025
Coarse Sand	kg	313,500.00	267.838	0.0046	1.232	0.0053	1.420
Portland Cement	kg	91,500.00	78.173	0.882	68.949	0.0316	2.470
Diesel	kg	149.39	0.128	0.237	0.030	0.1562	0.020
Total					72.699		11.935
Mixing the Raw Materials							
Cloth gloves	kg	5.04	0.004	2.11	0.008	3.3929	0.014
Tap water	m^3	139.34	0.119	0.541	0.064	-	-
Total					0.072		0.014
Conveying the Mixture to the Molding Station							
None	-	-	-	-	-	-	-
Total					-		-
Molding the Concrete Block							
None	-	-	-	-	-	-	-
Total					-		-
Naturally Curing the Concrete Block							
Tap water	m^3	124.657	0.107	0.541	0.058	-	-
Total					0.058		-
Total GHG Emissions for All 5 Steps of the Production Process					72.829		11.949

Table A6. GHG emissions in the production operations substage of the product production stage in the product life cycle.

Item	Resource Amount			Production Operations Substage	
	Unit	Quantity (2023)	Quantity per FU	Emission Factor ($kgCO_2eq$/unit)	Emission ($kgCO_2eq$)
Inspecting and Preparing Raw Materials					
Diesel	L	179.99	0.154	2.9793	0.459
Total					0.459
Mixing the Raw Materials					
Electricity	kWh	2,603.04	2.224	0.5986	1.331
Total					1.331
Conveying the Mixture to the Molding Station					
Electricity	kWh	2,398.96	2.050	0.5986	1.227
Total					1.227
Molding the Concrete Block					
None	-	-	-	-	-
Total					-
Naturally Curing the Concrete Block					
None	-	-	-	-	-
Total					-
Total GHG Emissions for All 5 Steps of the Production Process					3.017

Table A7. GHG emissions in the waste transportation and disposal substage of the product production stage in the product life cycle.

Item	Process Waste Amount			Waste Transportation Substage		Waste Disposal Substage	
	Unit	Quantity (2023)	Quantity per FU	Emission Factor ($kgCO_2eq$/unit)	Emission (kgCO2eq)	Emission Factor ($kgCO_2eq$/unit)	Emission ($kgCO_2eq$)
Inspecting and Preparing Raw Materials							
None	-	-	-	-	-	-	-
Total					-		-
Mixing the Raw Materials							
Cloth Gloves	kg	5.04	0.004	0.0040	0.000	2.0000	0.008
Total					0.000		0.008
Conveying the Mixture to the Molding Station							
None	-	-	-	-	-	-	-
Total					-		-
Molding the Concrete Block							
Broken concrete blocks	kg	191,909.97	163.958	0.0043	0.705	0.0000	0.000
Total					0.705		0.000
Naturally Curing the Concrete Block							
None	-	-	-	-	-	-	-
Total					-		-
Total GHG Emissions for All 5 Steps of the Production Process					0.705		0.008

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