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Carbon Footprint Assessment of a Bore Pile Contractor: A Case Study from Thailand

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Abstract:

Introduction: While assessments of organizational carbon footprint (CFO) are common across various sectors, studies specifically examining the CFO of construction organizations, especially bored pile contractors, remain scarce. This study evaluated the carbon footprint of a Thai bored pile contractor in 2022, during which 146 projects were completed across 20 provinces, involving 3,454 bored piles (1,998.90 m^3), 122,058.04 kg of reinforcement steel, and 1,832.62 m^3 of ready-mix concrete.

Methods: The carbon footprint assessment covered both the construction unit and the head office, adhering to the Thailand Greenhouse Gas Management Organization guidelines.

Results: The total carbon footprint was 712.099 tCO_2e, comprising Scope 1 direct emissions (66.231 tCO_2e, 9.30%), Scope 2 emissions from electricity (2.886 tCO_2e, 0.4%), and Scope 3 other indirect emissions (642.982 tCO_2e, 90.29%). Construction activities accounted for 706.234 tCO_2e (99.18%), while office operations contributed only 5.865 tCO_2e (0.82%). Emission intensities were 36.06 $kgCO_2e/m^3$ for bored pile drilling, 1.16 $kgCO_2e/kg$ for reinforcement steel, and 268.62 $kgCO_2e/m^3$ for ready-mix concrete. Construction materials, particularly ready-mix concrete and deformed bars, were the main contributors (634.150 tCO_2e, 89.05%).

Discussion: GHG emissions were primarily associated with construction materials, especially ready-mix concrete and reinforcement steel. These two materials were also overused by 9.30% and 8.94%, respectively, indicating opportunities to improve resource efficiency.

Conclusion: The findings highlight the importance of enhancing resource efficiency, prioritizing environmentally friendly products, and sourcing materials locally as key strategies to reduce GHG emissions. The study also provides benchmarks for bored pile contractors to measure environmental impact and promote sustainability in the construction sector.

Keywords: Bored pile, Corporate carbon footprint (CCF), Carbon footprint of organization (CFO), Greenhouse gas, Sustainability, Concrete.

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1. INTRODUCTION

The assessment of an organization's Carbon Footprint (CFO), also referred to as the Corporate Carbon Footprint (CCF), is a critical methodology for quantifying greenhouse gas (GHG) emissions. This approach applies across various levels, including individual companies, industries, and national frameworks, providing a standardized measure of emissions and their sources. At the organizational level, CFO assessments comprehensively evaluate GHG emissions while identifying key emission sources. This essential data enables businesses to develop targeted strategies for managing and reducing emissions, ultimately enhancing long-term sustainability. As global environmental standards tighten and carbon-related trade regulations become more stringent, businesses face increasing pressure to adopt sustainable practices. At the same time, consumers, business partners, and investors are prioritizing environmentally friendly products and ESG (Environmental, Social, and Governance) criteria. In response to these evolving demands, companies that conduct CFO assessments and implement effective GHG management strategies can strengthen their competitive position, expand market access, and attract investment [1].

Beyond benefiting individual organizations, CFO research is vital in promoting sustainability at the industry level. Publicly disclosing CFO findings not only enhances transparency and accountability but also serves as a valuable resource for industry peers. It enables similar businesses to develop effective strategies for reducing greenhouse gas emissions. CFO research contributes to collective progress toward a low-carbon future by supporting sustainability goals in the industry.

The urgency to reduce emissions has intensified in recent years. In 2022, global GHG emissions reached 53.8 Gt CO_2e, reflecting a 1.4% increase (or 730 Mt CO_2e) from 2021 levels [2]. The construction sector, encompassing material production and transportation, accounted for approximately 11% of these emissions [3]. Given this significant contribution, countries striving for net-zero targets, including Thailand, must prioritize research on the carbon footprint of construction-related organizations to develop effective mitigation strategies.

Foundation structures are fundamental to buildings, as they bear and distribute structural loads to the ground. Poorly designed or constructed foundations can lead to settlement, cracking, or structural failure. In Thailand, deep foundation work, including bored pile construction, is typically carried out by specialized contractors. With the continuous expansion of the construction sector, the number of foundation contractors has steadily increased. In 2023, Thailand’s Department of Business Development reported 556 registered and active foundation and piling contractors, up from 397 in 2022 and 379 in 2021. These businesses collectively generated over 15.12 billion baht (approximately $ 447.75 million) in revenue in 2023 [4].

Bored piles are widely used in Thailand as part of deep foundation systems, with demand increasing alongside the growth of the construction industry. This expansion has increased the number of small and medium-sized contractors specializing in bored pile construction, particularly those producing small-diameter bored piles (0.25–0.50 meters). These piles are commonly used in residential and small-scale projects, which constitute a significant portion of Thailand’s construction activities. Given their widespread use, assessing the CFO of these contractors is essential for fostering sustainable practices and developing effective emission reduction strategies within Thailand’s construction sector.

A review of prior research reveals a significant gap in CFO studies focusing on construction organizations, particularly bored pile contractors. Most existing CFO assessments have been conducted in the education sector. For instance, the carbon footprint of the Faculty of Agriculture at the University of Ruhuna in Sri Lanka has been analyzed [5]. At the same time, the Faculty of Environment and Resource Studies at Mahidol University in Thailand has also been examined [6]. Similarly, CFO studies have been conducted on universities in Spain, Colombia, Italy, Greece, and Thailand [7-11].

CFO assessments in other industries remain relatively scarce. Notable examples include studies on a telecommunications company in Slovenia [12], a wine company in Italy [13], and an electrode manufacturing company in Mexico [14]. Additional research includes studies on a beverage factory in Thailand [15], a denim-washing company in Turkey [16], and a football club [17].

While specific research assessing the CFO of bored pile contractors is lacking, several construction engineering and management studies have investigated greenhouse gas (GHG) emissions associated with bored pile construction.

For instance, a case study was conducted on the environmental emissions caused by construction equipment during the pile foundation process [18]. The research analyzed 84 piles of 750 mm in diameter and approximately 20 meters in depth, covering emissions from four categories of machinery: excavators, piling rigs, crawler cranes, and concrete pumping trucks [18]. A life cycle analysis of concrete bored piles identified that the primary sources of CO_2 emissions were the combustion of fuel in machinery and the transportation of raw materials [19].

Similarly, case studies have examined the environmental impact of machinery and material usage in bored pile construction, focusing on the average GHG emissions associated with equipment used for each project and offering comparisons across multiple projects [20]. Life cycle analysis has been applied to calculate the carbon footprint of helical piles in Brasília [21]. A comparison of emissions generated by prestressed pipe foundations and cast-in-situ pile foundations concluded that prestressed concrete pipe piles generally resulted in lower emissions [22]. In another relevant study, a cast-in-situ deep foundation system for a manufacturing plant was analyzed, emphasizing the critical role of accurately determining the Unconfined Compressive Strength (UCS) of pile materials, which directly affects pile design and the corresponding

GHG emissions [23]. Furthermore, an advanced algorithm has been developed to optimize the environmental impacts of concrete piles, whether bored or driven, in varying soil conditions by adjusting design parameters such as concrete grade, steel-to-concrete ratio, and pile slenderness ratio [24].

Despite the valuable insights provided by these studies, their primary focus has been on emissions directly arising from bored pile products, specific construction activities, or particular pieces of equipment. They often overlook indirect emissions generated by supporting functions, such as back-office operations. Additionally, methodological inconsistencies influence the comprehensiveness and accuracy of the reported emissions. While some studies base their findings on secondary data—such as emission factors per unit length of concrete piles—others rely on a single pile as the reference, which may not account for variations under different conditions. Using estimated rather than recorded data for material and resource consumption further raises concerns about the reliability of some results.

These limitations highlight the need for CFO research in the construction sector, particularly among bored pile contractors in Thailand, where such studies are currently limited. To address this gap, the present study evaluates and analyzes the CFO of a bored pile contractor, adopting a comprehensive approach that includes emissions from all supporting functions under the contractor's control. Unlike previous studies that rely on estimated or secondary data, this research is based on actual construction material consumption data recorded by the case study company throughout the monitoring period, ensuring greater accuracy and reliability in reported emissions.

Building on preliminary GHG emission data presented at the 29th National Convention on Civil Engineering, organized by the Engineering Institute of Thailand [25], this study aims to provide deeper insights into the topic. The findings are expected to offer practical benefits to bored pile contractors in Thailand and beyond as a valuable resource for improving emission management practices and promoting sustainability across the industry.

1.1. Case Study

The case study organization for this research is J.S. Union Construction Limited Partnership, a bored pile contractor in Thailand specializing in small-diameter bored piles (0.25–0.50 meters in diameter). The company provides three main types of contracts: bored pile drilling, bored pile drilling with the supply of reinforcement steel, and bored pile drilling with the supply of reinforcement steel and concrete. When contracted exclusively for bored pile drilling, it also takes responsibility for labor related to installing reinforcement steel and concrete casting.

The company operates through two primary units: the construction unit and the head office. The construction unit manages bored pile projects under client contracts, utilizing two modified six-wheel drilling trucks (Fig. **1**). Each truck is operated by a team of one supervisor and five workers. Additionally, a Sport Utility Vehicle (SUV) is assigned to the project manager for travel between the head office and construction sites, as well as for use during on-site stays. All vehicles, including drilling trucks and SUVs, are equipped with air conditioning systems. The head office, located in Mueang District, Uttaradit Province, Thailand, is a two-story building serving as a home office, with a usable area of 360 square meters. It is staffed by two employees who handle back-office operations. The office is equipped with six air conditioning units: one 18,000 BTU unit using R-32 refrigerant and five 13,000 BTU units using R-22 refrigerant.

Fig. (1). A drilling truck used by the company.

The company's operations are not confined to Uttaradit Province. It frequently undertakes projects in neighboring provinces and occasionally in locations as far as 800 kilometers away. The supervisor and workers travel together in drilling trucks from the head office to the site for non-local projects. In contrast, the project manager follows in the SUV to coordinate with clients and oversee the quality of work. Project durations vary depending on the study's scope and calculation approach, typically ranging from 3 to 60 days, with an average duration of approximately 5 days. During on-site work, the team resides in temporary tents at the project location. Upon completion, the team returns to the head office.

The bored pile construction process follows six key steps. First, the center of the pile is identified and marked. Then, a guide hole approximately 2 meters deep is drilled using an auger to prepare for the installation of casing. Next, a steel casing is inserted into the guide hole, rotated, and pressed into place using the drilling truck's hydraulic system. Once the casing is securely positioned, soil excavation begins, and the auger extracts the removed soil. The pre-tied reinforcement cage is carefully lowered into the borehole, followed by the pouring of concrete to form the pile. Finally, the casing is gradually rotated and lifted out of the borehole to prevent soil collapse or displacement of the reinforcement cage. The primary materials used during the process include diesel fuel, steel reinforcement, and concrete.

The monitoring period for this case study spanned from January 1 to December 31, 2022. During this time, the company completed 146 projects across 20 provinces. These included 19 projects involving only bored pile drilling, one project involving bored pile drilling with the supply of reinforcement steel, and 129 projects involving bored pile drilling with the supply of both reinforcement steel and concrete. Over the years, a total of 3,454 bored piles were drilled, with a cumulative drilling volume of 1,998.90 cubic meters. Additionally, 122,058.04 kilograms of reinforcement steel and 1,832.62 cubic meters of concrete were supplied.

1.2. Scope of the Study and Calculation Approach

This study assessed the carbon footprint of the case study company, focusing on two operational units under its control: the construction unit and the head office. The assessment adhered to the guidelines established by the Thailand Greenhouse Gas Management Organization [26], which are consistent with international standards such as ISO 14064-1 [27] and the Greenhouse Gas Protocol Corporate Accounting and Reporting Standard [28]. Under the TGO framework, GHG emissions are classified into three scopes: Scope 1 encompasses direct emissions from sources owned or controlled by the organization; Scope 2 addresses indirect emissions from the consumption of imported electricity, heat, or steam; and Scope 3 includes other indirect emissions resulting from organizational activities but originating from sources controlled by external entities, with reporting limited to categories deemed significant to the organization.

Following the TGO framework, this study reported the GHG emissions as CO_2-equivalent (CO_2e) values without differentiating specific gases. The emissions from all three scopes were calculated using a standardized Eq. (**1**):

$$\text{GHG Emissions} = \text{Activity Data} \times \text{Emission Factor}, \quad (1)$$

In this equation, "GHG Emissions" refers to the total greenhouse gas emissions produced by a specific activity, measured in tons of CO_2 equivalent (tCO_2e). "Activity Data" refers to quantitative information related to the emission-producing activity, including the amount of resources consumed or transportation details. The "Emission Factor (EF)" is a coefficient that converts activity data into GHG emissions.

An example of calculating GHG emissions using Eq. (**1**) is as follows: Consider the GHG emissions resulting from the diesel consumption of drilling trucks. In this case, the total diesel consumption is 21,334.80 liters. The combustion of diesel fuel for energy production generates greenhouse gases at a rate of 2.7406 $kgCO_2e$ per liter. By substituting these values into Eq. (**1**), the GHG emissions from diesel consumption by drilling trucks can be calculated as follows:

$$\begin{aligned} \text{GHG Emissions} &= \text{Activity Data} \times \text{Emission Factor} \\ &= 21{,}334.80 \text{ liters} \times 2.7406 \text{ kgCO}_2\text{e/liter} \\ &= 58{,}470 \text{ kgCO}_2\text{e} \\ &= 58.470 \text{ tCO}_2\text{e} \end{aligned}$$

2. MATERIALS AND METHODS

A structured six-step approach was employed to achieve the study's objectives. Each step was designed to systematically identify, quantify, and analyze the GHG emissions across the two utility units of the company, addressing activities related to Scopes 1, 2, and 3.

2.1. Step 1: Identification and Categorization of Current Activities

The first step involved a comprehensive review of processes and data from both utility units to identify and categorize activities contributing to GHG emissions under Scopes 1, 2, and 3. The review revealed that these activities fell into two categories under Scope 1, one under Scope 2, and five under Scope 3.

2.2. Step 2: Identification of Required Data Types

The second step focused on identifying the specific types of activity data necessary for GHG emission calculations. Each activity was evaluated to determine the availability and accessibility of data, either through internal records or data collection efforts. This step ensured that the study's calculations were accurate, consistent, and replicable, forming a robust foundation for the carbon footprint assessment.

2.3. Step 3: Collection of Activity Data

In the third step, the necessary activity data were collected from the company. Primary sources included existing documents such as receipts, product specifications, and internal reports. For cases where documented data were unavailable, interviews were conducted with relevant personnel to gather the required information. This step was critical to ensuring the comprehensiveness of the dataset used for GHG emission calculations.

2.4. Step 4: Selection or Calculation of GHG Emission Factors

The fourth step involved obtaining reliable emission factors for each identified activity. These factors were sourced from external databases or calculated when necessary, emphasizing the currency and reliability of the data. The accuracy of emission factors is critical, as they translate activity data into quantifiable GHG emissions, serving as the basis for the study's calculations.

2.5. Step 5: Calculation of GHG Emissions

In this phase, the collected activity data were converted into GHG emissions using the appropriate emission factors. The results were expressed in metric tons of CO_2 equivalent ($MtCO_2e$), providing a standardized measure of the organization's carbon footprint across different activities and scopes.

2.6. Step 6: Analysis of GHG Emission Data

The final step entailed thoroughly analyzing the GHG emission data collected during the study. Emissions were categorized by scopes, utility units, and types of work to provide a holistic overview and to identify critical emission hotspots. The analysis further quantified emissions from construction-related activities and office operations and calculated emission intensities for bored pile drilling, reinforcement steel supply, and ready-mix concrete supply. Additionally, emissions were classified by resource types and emission stages, offering insights into resource-specific emissions and revealing resource hotspots.

2.7. Activity Data, GHG Emission Factors, and GHG Emissions

The activity data, GHG emission factors, and calculated emissions obtained in this study are summarized in Tables **1**-**8**. Activity data were collected from various sources. For example, the quantities of diesel fuel for drilling trucks, gasoline for the project supervisor's SUV, concrete, reinforcement steel, steel tying wire, hydraulic oil, and electricity were gathered from supplier receipts. Data on the types of vehicles used for transporting concrete, reinforcement steel, waste, and staff members' personal vehicles were collected through interviews. Travel distances for vehicles were measured using Google Maps. The volume of refrigerant leakage was estimated based on the capacity of refrigerant containers, while the quantities of photocopy paper and toilet paper were collected from office material requisition logs. Garbage quantities, measured in kilograms, were estimated based on the frequency of waste disposal trips and the average weight of garbage per trip, which was determined through two rounds of random sampling.

For selecting GHG emission factors, certified data from product suppliers, the Thai National Life Cycle Inventory database (TLCI), peer-reviewed studies, life cycle assessment software, and international organizations were prioritized. Emissions for each activity were calculated using Eq. (**1**). Activity data reported in different measurement units were converted to ensure consistency with the relevant emission factor, and the resulting GHG emissions were then converted from kilograms of CO_2-equivalent ($kgCO_2e$) into metric tons of CO_2-equivalent (tCO_2e).

This study classified GHG emissions from various activities by scope and sub-scope according to the framework of the Thailand Greenhouse Gas Management Organization (TGO). Scope 1 emissions, representing direct emissions from sources owned or controlled by the organization, are presented in Tables **1** and **2**. Scope 2 emissions, which include indirect emissions from the consumption of imported electricity, heat, or steam, are shown in Table **3**. Scope 3 emissions, covering other indirect emissions, are detailed in Tables **4**-**8**.

2.7.1. Emissions from Activities within Scope 1-2 (Direct GHG Emissions from Mobile Combustion)

Emissions from mobile combustion, arising from two activities under the construction unit, are presented in Table **1**. The total GHG emissions from these activities amounted to 63.444 tCO_2e.

2.7.2. Emissions from Activities within Scope 1-4 (Direct GHG Emissions from Fugitive Emissions)

Emissions from fugitive sources, arising from six activities—three under the construction unit and three under the office—are summarized in Table **2**. The total GHG emissions from these activities amounted to 2.787 tCO_2e.

To estimate refrigerant leakage from air-conditioning units, the refrigerant container capacity of each unit was multiplied by its leakage rate, and the result was adjusted based on the total number of air-conditioning units. The container capacities and unit counts were obtained through surveys, while leakage rates were sourced from Tables **3**-**6** of the TGO publication [29].

The survey revealed that drilling trucks and SUVs were equipped with air-conditioning units containing refrigerant capacities of 1.00 kg and 0.50 kg, respectively. In the office, the air-conditioning units had refrigerant capacities of 0.60 kg for an 18,000 BTU unit and 0.78 kg for each of the five 13,000 BTU units. According to the TGO publication, leakage rates were assumed to be 20% for mobile air conditioning systems and 15% for standalone commercial air conditioning units.

To estimate the CH_4 leakage from domestic wastewater treatment, the daily CH_4 leakage per person was multiplied by the total number of workers and company officer man-days. According to the IPCC guidelines [30], the CH_4 leakage rate was estimated to be 0.012 kg per person per day.

Once the quantities of refrigerant leakage and CH_4 leakage for each activity were determined, the associated GHG emissions were calculated by multiplying these values by their respective emission factors.

Table 1. Activity data, GHG EFs, and GHG emissions of activities within scope 1-2.

Activity	Unit	Quantity	Quantity Data Source	EF ($kgCO_2e$/Unit)	EF Data Source	Emission (tCO_2e)
The construction unit						
Diesel consumption (drilling trucks)	Litre	21,334.80	Supplier receipts	2.7406	TGO. (2022b)	58.470
Gasoline consumption (sports utility vehicle)	Litre	2,221.32		2.2394	TGO. (2022b)	4.974

Table 2. Activity data, GHG EFs, and GHG emissions of activities within scope 1-4.

Activity	Unit	Quantity	Quantity Data Source	EF ($kgCO_2e$/Unit)	EF Data Source	Emission (tCO_2e)
The construction unit						
Leakage of R134a (air conditioner of two drilling tucks; 1,000-gram container)	kg	0.40	Calculation	1,300.0000	TGO. (2022b)	0.520
Leakage of R134a (air conditioner of an SUV; 500-gram container)	kg	0.10		1,300.0000	TGO. (2022b)	0.130
Leakage of CH_4 (septic tank)	kg	28.80		28.0000	TGO. (2022a)	0.806
The Office						
Leakage of R-32 (one 18,000 BTU air conditioner; 600-gram container)	kg	0.09	Calculation	677.0000	TGO. (2022b)	0.061
Leakage of R-22 (five 13,000 BTU air conditioners; 780-gram container)	kg	0.59		1,810.0000	TGO. (2022b)	1.068
Leakage of CH_4 (septic tank)	kg	7.20		28.0000	TGO. (2022a)	0.202

Table 3. Activity data, GHG EFs, and GHG emissions of activities within scope 2-1.

Activity	Unit	Quantity	Quantity Data Source	EF ($kgCO_2e$/Unit)	EF Data Source	Emission (tCO_2e)
The Office						
Electricity consumption	kWh	5,774.00	Supplier receipts	0.4999	TGO. (2022b)	2.886

Table 4. Activity data, GHG EFs, and GHG emissions of activities within scope 3-1.

Activity	Unit	Quantity	Quantity Data Source	EF ($kgCO_2e$/Unit)	EF Data Source	Emission (tCO_2e)
The construction unit						
R134a	kg	0.50	-	103.3316	TGO. (2022c)	0.052
Hydraulic oil consumption	Liters	198.00	Supplier receipts	2.9120	TGO. (n.d.) (PTT Public Company Limited)	0.577
Reinforcement steel consumption (deformed bar)	kg	113,598.30		1.060	TGO. (n.d.) (Millcon Steel Public Company Limited)	120.414
Reinforcement steel consumption (round bar)	kg	19,816.83		0.6700	TGO. (n.d.) (Chow Steel Public Company Limited)	13.277
Tying wire consumption	kg	1,900.00		0.1730	TGO. (n.d.) (Pyro Energie Company Limited)	0.329
Ready-mix concrete consumption	m^3	1,996.50		243.0000	TGO. (n.d.) (The Concrete Products and Aggregate Company Limited)	485.150
The Office						
R-32	kg	0.09	-	86.0400	Chinese academy of environmental planning	0.008
R-22	kg	0.59	-	75.7860	TGO. (2022c)	0.045
Copier paper consumption	Sheet	1,000.00	Office material requisition logs	0.0115	TGO. (n.d.) (Phoenix Pulp & Paper Public Company Limited)	0.012
Toilet paper consumption (16 m / Roll)	Roll	48.00		0.0839	TGO. (n.d.) (Kimberly-Clark Thailand Company Limited)	0.004

Table 5. Activity data, GHG EFs, and GHG emissions of activities within scope 3-3.

Activity	Unit	Quantity	Quantity Data Source	EF ($kgCO_2e$/Unit)	EF Data Source	Emission (tCO_2e)
The construction unit						
Diesel production	kg	17,750.55	Supplier receipts	0.2370	TGO. (n.d.) (Bangchak Corporation Public Company Limited)	4.207
Gasoline production	kg	1,654.88		0.3440	TGO. (n.d.) (Bangchak Corporation Public Company Limited)	0.569
Transporting diesel and gasoline						
22-wheeler truck and trailer 100% loading (max load 32.00 t) (Oil refinery to gas station)	t-km	10,743.18	Supplier receipts /google map	0.0659*	TGO. (2022c)	0.707
22-wheeler truck and trailer 0% loading (max load 32.00 t (Gas station oil to refinery)	trip-km	482.19		1.0206	TGO. (2022c)	0.492
The Office						
Electricity consumption (electricity loss during transmission)	kWh	5,774.00	Supplier receipts	0.0987	TGO. (2022b), TGO. (2022c)	0.570

2.7.3. Emissions from Activities within Scope 2-1 (Indirect GHG Emissions from Purchased Electricity)

Indirect emissions from purchased electricity arising from office electricity consumption are presented in Table **3**. According to the Provincial Electricity Authority invoice, the total electricity usage in 2022 was 5,774.00 kWh, resulting in GHG emissions of 2.886 tCO_2e.

2.7.4. Emissions from Activities within Scope 3-1 (Indirect GHG Emissions from Purchased Goods and Services)

Indirect emissions from purchased goods and services, arising from ten activities—six under the construction unit and four under the office—are summarized in Table **4**. These activities collectively resulted in total GHG emissions of 619.868 tCO_2e.

To estimate GHG emissions from the acquisition and production of raw materials for hydraulic oil and related emissions under other sub-scopes, carbon footprint (CFP) data for hydraulic oil is essential. However, since the TGO database does not include CFP data for hydraulic oil, this study used data from a comparable product listed in the database—lubricant. According to the manufacturer, the CFP (business-to-customer) of lubricant is reported as 5.2000 kg CO_2e/l, with GHG emissions distributed as follows: 56% from raw material acquisition and production, 1% from distribution, and 43% from disposal. Based on these proportions, the estimated GHG emissions are 2.912 kg CO_2e/l for raw material acquisition and production, 0.052 kg CO_2e/l for distribution, and 2.236 kg CO_2e/l for disposal. These emission factors were then multiplied by the quantity of hydraulic oil used to calculate the GHG emissions assigned to each sub-scope: Scope 3-1, Scope 3-4, and Scope 3-5.

Similarly, since the TGO database lacks CFP data for 16-meter rolls of toilet paper but provides data for 300-meter rolls, this study estimated the GHG emissions for the shorter rolls based on the length ratio of the two roll sizes. According to the manufacturer, the CFP (business-to-customer) for a 300-meter roll is 2.28 kg CO_2e/roll, with GHG emissions attributed as follows: 69% to raw material acquisition and production, and 31% to disposal. Using these proportions, the estimated GHG emissions for a 16-meter roll are 0.0839 kg CO_2e/roll for raw material acquisition and production and 0.0377 kg CO_2e/roll for disposal. The total emissions associated with toilet paper use were then determined by applying these factors to the quantity consumed, categorizing them under Scope 3-1 and Scope 3-5.

2.7.5. Emissions from Activities within Scope 3-3 (indirect GHG Emissions from Fuel and Energy-related Activities)

Indirect emissions from fuel- and energy-related activities, arising from five activities—three under the construction unit and two under the office—are summarized in Table **5**. The total GHG emissions from these activities totaled 6,672 tCO_2e.

To estimate the GHG emissions associated with diesel and gasoline production, the fuel quantities, initially provided in liters, were first converted to kilograms using their respective mass densities: 0.860 kg/L for diesel and 0.725 kg/L for gasoline. These values were then multiplied by their corresponding emission factors, reported in $kgCO_2e$ per kg, to calculate the total GHG emissions from fuel production.

The estimation of GHG emissions from fuel transportation for the construction unit began by converting fuel volumes (in liters) to weights (in kilograms). With 146 projects across 20 provinces, distances from Bangkok (the refinery location) to gas stations were determined and multiplied by the fuel volumes to calculate the total transportation volume in tons-kilometers. Fuel was transported using 22-wheeler trucks with a 32.00 t capacity and an adequate load capacity of 22.28 t (after accounting for the 9.72 t empty tank weight). The number of trips was obtained by dividing the total fuel weight by 22.28 t/trip, and the total trip-km was calculated by multiplying the number of trips by the distances. Return trip emissions (for empty trucks) were included, using the exact distances. The GHG emission factor for outbound trips was adjusted using a scaling factor of 1.436 (32.00 t/22.28 t), resulting in an increased emission factor from 0.0459 to 0.0659 kg CO_2e/t-km.

2.7.6. Emissions from Activities within Scope 3-4 (Indirect GHG Emissions from Upstream Transportation and Distribution)

Indirect emissions from upstream transportation and distribution, arising from four activities—three under the construction unit and one under the office—are summarized in Table **6**. The GHG emissions from these activities totaled 14.996 tCO_{2e}.

Table 6. Activity data, GHG EFs, and GHG emissions of activities within scope 3-4.

Activity	Unit	Quantity	Quantity Data Source	EF ($kgCO_2$e/Unit)	EF Data Source	Emission (tCO_2e)
The construction unit						
Transporting hydraulic oil	liters	198.00	Supplier receipts	0.052	TGO. (n.d.) (PTT Public Company Limited)	0.010
Transporting reinforcement steel and trying wire						
10-wheeler crane truck 0% loading (max load 16.00 t) (Vendor's store to project)	km	1,686.27	Supplier receipts /google map	0.5977	TGO. (2022c)	1.008
10-wheeler crane truck 0% loading (max load 16.00 t) (Project to vendor's store)	km	1,686.27		0.5977	TGO. (2022c)	1.008
22-wheeler truck 100% loading (max load 32.00 t) (Factory to vendor's store)	t-km	75,029.53		0.0459	TGO. (2022c)	3.444
22-wheeler truck 0% loading (max load 32.00 t) (Vendor's store to factory)	trip-km	2,344.58		1.0206	TGO. (2022c)	2.393
Transporting ready-mix concrete						
10-wheeler concrete mixer 75% loading (max load 16.00 t) (Concrete plant to project)	t-km	48,184.80	Supplier receipts /google map	0.0625	TGO. (2022c)	3.012
10-wheeler concrete mixer 50% loading (max load 16.00 t) (Concrete plant to project)	t-km	8,159.82		0.0918	TGO. (2022c)	0.749
10-wheeler concrete mixer 0% loading (max load 16.00 t) (Project to the concrete plant)	trip-km	5,320.00		0.6316	TGO. (2022c)	3.360
The Office						
Transporting copier paper and toilet paper						
4-wheeler truck 0% loading (max load 7.00 t) (Vendor's store to project)	km	20.00	Office material requisition logs/google map	0.3131	TGO. (2022c)	0.006
4-wheeler truck 0% loading (max load 7.00 t) (Project to vendor's store)	km	20.00		0.3131	TGO. (2022c)	0.006
10-wheeler box truck 100% loading (max load 16.00 t) (Factory to vendor's store)	t-km	4.37		0.0454	TGO. (2022c)	0.000
10-wheeler box truck 0% loading (max load 16.00 t) (Vendor's store to factory)	trip-km	0.27		0.5747	TGO. (2022c)	0.000

Note: *Adjustments were made according to the details specified in the content.

For estimating GHG emissions from upstream transportation, key data inputs included the weight of transported resources, transportation distance, and emission factors for different transport modes. The emission factors varied based on vehicle type and the percentage of load capacity utilized per trip.

Reinforcement steel and tying wire transportation involved two stages. First, delivery from vendors to project sites used 10-wheeler crane trucks (16.00 t capacity). Since deliveries were always under 8.00 t, each project required a single trip. GHG emissions were calculated using a 0% load emission factor, taking into account the distances between vendors and project sites. Second, transportation from the Bangkok factory to vendors used 22-wheeler trucks (32.00 t capacity). Total t-km was calculated by multiplying the material weight by the distances between Bangkok and the provinces where the projects were located. Return trips were assumed to be empty, with emissions calculated from trip-km. The number of trips was determined by dividing the total material weight by the truck's load capacity.

Concrete transportation from plants to project sites used 10-wheeler mixers (16.00 t capacity), typically carrying 5.00 m^3 of concrete (12.00 t, 75% capacity) or, occasionally, 8.00 t (50% capacity). Trip counts were obtained from supplier receipts.

For office supply transportation, the copier paper weight was determined by dividing the total number of sheets by 500 sheets per pack and multiplying by 2.50 kg/pack. The weight of the toilet paper was calculated by multiplying the total number of rolls by 0.056 kg/roll. Deliveries from the vendor to the office used 4-wheeler trucks, each carrying less than 3.50 t (50% capacity). With a delivery distance of 10.00 km and two trips recorded, GHG emissions were estimated using the emission factor for 0% loading. Transportation from the factory in Samut Sakhon to the vendor in Uttaradit (568.80 km) used 10-wheeler box trucks (16.00 t capacity), with trips calculated based on total paperweight.

2.7.7. Emissions from Activities within Scope 3-5 (Indirect GHG Emissions from Waste Generated in Operations)

Indirect emissions from waste generated in operations, arising from four activities—two under the construction unit and two under the office—are summarized in Table **7**. The GHG emissions from these activities totaled 0.529 tCO_{2e}.

To estimate the GHG emissions and emission factors associated with reinforcement steel waste, the quantity of waste was first determined by subtracting the amount of reinforcement steel specified in the design drawings from the total purchased. Interview data indicated that drilling trucks initially transported reinforcement steel waste from the bored pile construction site to the office. Then, it was transported to a recycling shop 0.90 km from the office every month using a 4-wheeler truck. GHG emissions were calculated based on this information, and the emission factor shown in Table **7** was derived by dividing the total emissions from transporting the reinforcement steel waste by its total weight.

For garbage-related GHG emissions, the quantity of garbage was estimated through random sampling and waste weighing. The emission factor for garbage was determined by summing the emission factor for municipal waste collection and transportation (0.0143 kg CO_2e/kg) with the emission factor for sanitary landfill disposal of municipal solid waste (0.7933 kg CO_2e/kg). Finally, GHG emissions were calculated by multiplying the total quantity of garbage by the corresponding emission factor.

2.7.8. Emissions from Activities within Scope 3-7 (Indirect GHG Emissions from Employee Commuting)

Indirect emissions from employee commuting, arising from three groups of activities under the office, are presented in Table **8**. The GHG emissions from these activities totaled 0.917 tCO_{2e}.

To estimate GHG emissions from employee commuting, the vehicle type of each employee was first identified. The results showed that employees commuted using two types of vehicles: motorcycles fueled with gasoline and pickup trucks running on diesel. Commuting distances per trip for supervisors and workers were then obtained through interviews. Based on this information, the total commuting distance for each employee was calculated by considering both their trip distance and the number of trips to the office. The total fuel consumption (in liters) was determined by dividing the total commuting distance by the average fuel consumption rates: 37.640 km/L for a 4-stroke motorcycle and 11.111 km/l for a 1-ton personal pickup truck. Then, GHG emissions from fuel consumption and fuel production were calculated by multiplying the total fuel consumption by the corresponding emission factors for each type of fuel.

Finally, GHG emissions from transporting fuel used for employee transportation were estimated using total fuel weight, the distance between Bangkok and Uttaradit (516.80 km), and the number of trips. The trip count was determined by dividing total fuel weight by the adjusted truckload capacity of 22.28 t.

3. RESULTS AND DISCUSSION

The greenhouse gas (GHG) emission data obtained from various activities and categorized by different scopes are presented in Tables **1**-**8**. These data were systematically analyzed and grouped according to the responsible utility units for each activity. For the construction unit, emissions were further disaggregated by specific types of work performed. The aggregate GHG emissions across all scopes, utility units, and work categories are summarized in Table **9**, while Fig. (**2**) visually depicts GHG emissions across the different scopes.

Table 7. Activity data, GHG EFs, and GHG emissions of activities within scope 3-5.

Activity	Unit	Quantity	Quantity Data Source	EF ($kgCO_2e$/Unit)	EF Data Source	Emission (tCO_2e)
The construction unit						
Hydraulic oil waste	Liter	198.00	Supplier receipts	2.2360	TGO. (n.d.) (PTT Public Company Limited)	0.443
Reinforcement steel waste	kg	10,705.51	Calculation	0.0006	Calculation	0.006
The Office						
Garbage	kg	96.00	Calculation	0.8076	TGO. (2022c)	0.078
Toilet paper consumption (16 m / Roll)	roll	48.00	Supplier receipts	0.0377	TGO. (n.d.) (Kimberly-Clark Thailand Company Limited)	0.002

Table 8. Activity data, GHG EFs, and GHG emissions of activities within scope 3-7.

Activity	Unit	Quantity	Quantity Data Source	EF ($kgCO_2e$/Unit)	EF Data Source	Emission (tCO_2e)
The Office						
Fuel consumption	-	-	-	-	-	-
Diesel consumption	Litre	92.16	Interviews and calculations	2.7446	TGO. (2022b)	0.253
Gasoline consumption	Litre	253.00		2.2394	TGO. (2022b)	0.567
Fuel production	-	-	-	-	-	-
Diesel production	kg	79.26	Supplier receipts	0.2370	TGO. (n.d.) (Bangchak Corporation Public Company Limited)	0.019
Gasoline production	kg	183.43		0.3440	TGO. (n.d.) (Bangchak Corporation Public Company Limited)	0.063
Transporting gasoline and diesel						
22-wheeler truck and trailer 100% loading (max load 32.00 t) (Oil refinery to gas station)	t-km	135.75	Supplier receipts /google map	0.0659	TGO. (2022c)	0.009
22-wheeler truck and trailer) 0% loading (max load 32.00 t (Gas station oil to refinery)	trip-km	6.09		1.0206	TGO. (2022c)	0.006

Table 9. Scopes, utility units, and types of work classify GHG emissions.

Activity	GHG Emission (tCO_2e/Year)				
	The Construction Unit			The Office	Total
	Bored Pile Drilling	Supply of Reinforcement Steel	Supply of Ready-mix Concrete		
Scope 1 Direct GHG Emissions					
Scope 1-2 Direct GHG Emissions from Mobile Combustion					
Diesel consumption	58.470	-	-	-	58.470
Gasoline consumption	4.974	-	-	-	4.974
Total GHG emissions from scope 1-2	63.444	-	-	-	63.444
Scope 1-4 Direct GHG Emissions from Fugitive Emissions					
Leakage of R134a	0.650	-	-	-	0.650
Leakage of R-22	-	-	-	0.061	0.061

(Table 9) contd.....

Activity	GHG Emission (tCO_2e/Year)				
	The Construction Unit			The Office	Total
	Bored Pile Drilling	Supply of Reinforcement Steel	Supply of Ready-mix Concrete		
Leakage of R-32	-	-	-	1.068	1.068
Leakage of CH_4	0.806	-	-	0.202	1.008
Total GHG emissions from scope 1-4	1.456	-	-	1.331	2.787
Total GHG Emissions from Scope 1	64.900	-	-	1.331	**66.231**
Scope 2 Energy Indirect GHG Emissions					
Scope 2 -1 Indirect GHG Emissions from Purchased Electricity					
Electricity consumption	-	-	-	2.886	2.886
Total GHG emissions from scope 2-1	-	-	-	2.886	2.886
Total GHG Emissions from Scope 2	-	-	-	2.886	**2.886**
Scope 3 Other Indirect GHG Emissions					
Scope 3-1 Indirect GHG Emissions from Purchased Goods and Services					
R134a	0.052	-	-	-	0.052
Hydraulic oil consumption	0.577	-	-	-	0.577
Reinforcement steel consumption (deformed bar)	-	120.414	-	-	120.414
Reinforcement steel consumption (round bar)	-	13.277	-	-	13.277
Tying wire consumption	-	0.329	-	-	0.329
Ready-mix concrete consumption	-	-	485.150	-	485.150
R-22	-	-	-	0.008	0.008
R-32	-	-	-	0.045	0.045
Copier paper consumption	-	-	-	0.012	0.012
Toilet paper consumption	-	-	-	0.004	0.004
Total GHG emissions from scope 3-1	0.629	134.020	485.150	0.069	619.868
Scope 3-3 Indirect GHG Emissions from Fuel-and Energy-Related Activities					
Diesel production	4.348	-	-	-	4.348
Gasoline production	0.554	-	-	-	0.554
Transporting diesel and gasoline	1.200	-	-	-	1.200
Electricity loss during transmission	-	-	-	0.570	0.570
Total GHG Emissions from Scope 3-3	6.102	-	-	0.570	6.672
Scope 3-4 Indirect GHG Emissions from Upstream Transportation and Distribution					
Transporting hydraulic oil	0.010	-	-	-	0.010
Transporting reinforcement steel and trying wire	-	7.853	-	-	7.853
Transporting ready-mix concrete	-	-	7.121	-	7.121
Transporting copier paper and toilet paper	-	-	-	0.012	0.012
Total GHG emissions from scope 3-4	0.010	7.853	7.121	0.012	14.996
Scope 3-5 Indirect GHG Emissions from Waste Generated in Operations					
Hydraulic oil	0.443	-	-	-	0.443
Reinforcement steel waste	-	0.006	-	-	0.006
Garbage	-	-	-	0.078	0.078
Toilet paper	-	-	-	0.002	0.002
Total GHG emissions from scope 3-5	0.443	0.006	-	0.080	0.529
Scope 3-7 indirect GHG emissions from employees' commuting					
Diesel consumption	-	-	-	0.253	0.253
Gasoline consumption	-	-	-	0.567	0.567
Diesel production	-	-	-	0.019	0.019
Gasoline production	-	-	-	0.063	0.063
Transporting diesel and gasoline	-	-	-	0.015	0.015
Total GHG emissions from scope 3-7	-	-	-	0.917	0.917
Total GHG emissions from scope 3	**7.184**	**141.879**	**492.271**	**1.648**	**642.982**
Total GHG emissions from scope 1 to 3	**72.084**	**141.879**	**492.271**	**5.865**	**712.099**

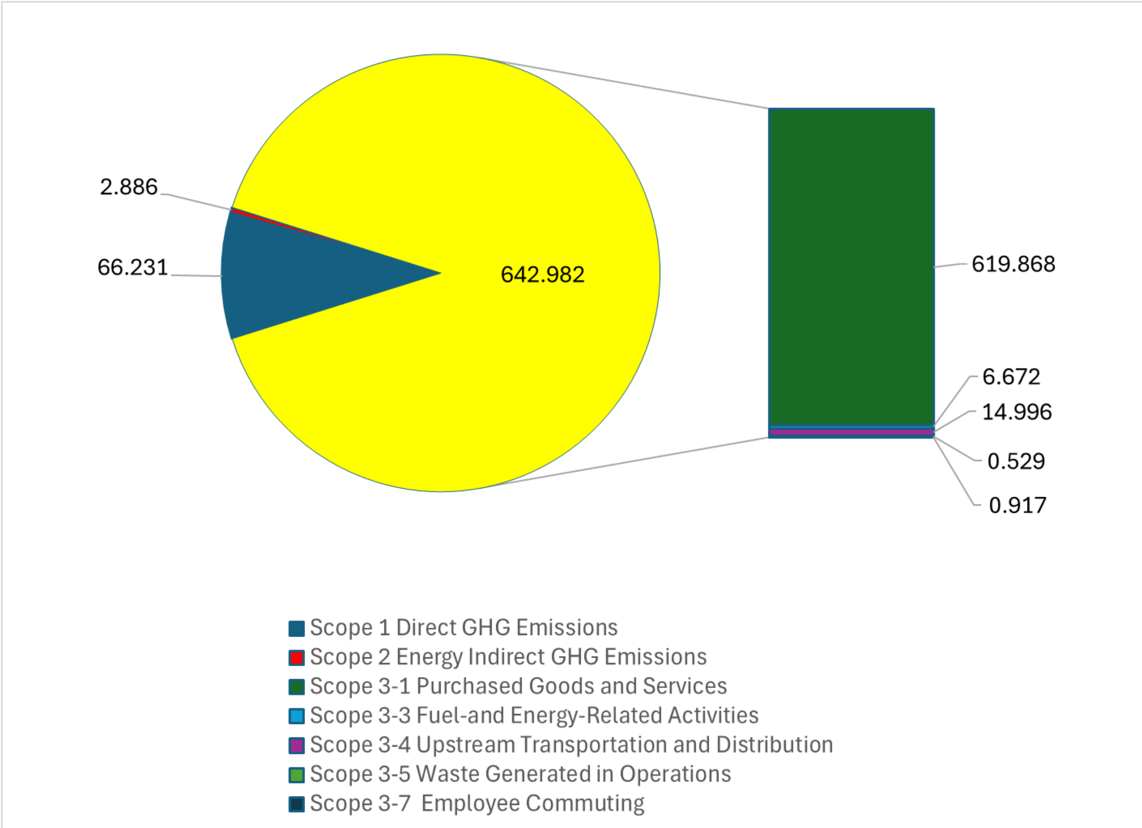

Fig. (2). GHG emissions across the different scopes.

As detailed in Table **9** and Fig. (**2**), the total greenhouse gas (GHG) emissions, or carbon footprint, of the case study bored pile contractor in 2022 totaled 712.099 tCO_2e. These emissions were distributed across the scopes as follows: Scope 1 emissions contributed 66.231 tCO_2e (9.30%), Scope 2 emissions were 2.886 tCO_2e (0.41%), and Scope 3 emissions dominated with 642.982 tCO_2e (90.29%). A closer examination of each sub-scope revealed that the top three emission sources were Scope 3-1 (purchased goods and services), Scope 1-2 (purchased electricity), and Scope 3-4 (upstream transportation and distribution), accounting for 619.868 tCO_2e (87.05%), 63.444 tCO_2e (8.91%), and 14.996 tCO_2e (2.11%), respectively. These three sub-scopes represented 98.06% of the company's total emissions. Based on these findings, it is clear that the company should prioritize strategies to control and reduce emissions, with a particular focus on these key sub-scopes.

The company can adopt similar approaches to mitigate emissions from Scope 3-1 and Scope 3-4. Specifically, enhancing resource efficiency would reduce both procurement volumes and transportation needs. The procurement process should also prioritize environmentally friendly materials and locally sourced resources, thereby reducing emissions associated with the production and transportation stages of resource extraction.

Addressing Scope 1-2 emissions—a significant challenge given their direct connection to the use of drilling trucks and SUVs, which are long-lived, high-value assets—requires both short- and long-term measures. In the short term, the company should conduct an in-depth study of drilling and driving operations to identify specific opportunities for reducing fuel consumption. Subsequently, operational guidelines should be developed to help users optimize fuel efficiency. The company may consider transitioning to alternative machinery and vehicles offering lower direct GHG emissions than the current fleet in the long term. These mitigation efforts are essential for achieving substantial emissions reductions and aligning with the company's long-term sustainability goals.

Due to the variability in the types and volumes of work assigned by clients each year, assessing a construction organization's GHG management performance based solely on absolute emissions can be misleading, as emissions naturally fluctuate with the scope of work. To address this issue, GHG emissions should be analyzed separately for construction operations, which are significantly influenced by project type and volume, and office activities, which remain relatively stable in terms of their emissions. Furthermore, when evaluating the GHG management performance of construction operations, the focus should shift from absolute emission values to emission intensities for each work category, as construction-related emissions are directly linked to project type and scale.

A comparison of emissions from construction-related activities and office activities, as shown in Table **9**, reveals a significant disparity. Construction-related activities under the control of the construction unit contributed 706.234 tCO_2e (99.18%) of the total emissions, while office activities accounted for only 5.865 tCO_2e (0.82%). Within the construction unit, activities directly associated with bored pile drilling—including equipment and labor transportation, reinforcement steel installation, and concrete casting—resulted in 72.032 tCO_2e emissions. In contrast, emissions from the supply of reinforcement steel and ready-mix concrete were considerably higher, at 141.879 t CO_2e and 492.271 t CO_2e, respectively. These findings underscore the need for the company to prioritize emission reduction efforts within the construction unit, particularly in areas related to the supply of reinforcement steel and concrete.

To gain deeper insights into emissions from construction activities, these emission data were analyzed alongside the company's 2022 operational data to calculate emission intensities. During 2022, the company completed 1,998.90 m^3 of bored pile drilling, supplied 122,058.04 kg of reinforcement steel, and delivered 1,832.62 m^3 of ready-mix concrete. The analysis revealed that bored pile drilling produced an average of 36.06 kg CO_2e per cubic meter. In comparison, the supply of reinforcement steel and ready-mix concrete generated 1.16 kg CO_2e per kilogram and 268.62 kg CO_2e per cubic meter, respectively. These calculated GHG emission intensities, along with the office's 2022 GHG emission data, provide critical benchmarks for managing and reducing emissions across the construction unit and the office in future operational years. Additionally, the emission intensity data offers valuable insights for estimating GHG emissions from bored pile construction and calculating the embodied carbon of building structures, ultimately guiding the adoption of more sustainable practices within the construction sector.

The data presented in Tables **1**-**8** were further categorized by resource group and type to assess the total GHG impact of each resource across four key stages: resource production, resource transportation, construction, and waste disposal. The consolidated findings are summarized in Table **10**, while Fig. (**3**) visually depicts GHG emissions categorized by resource type.

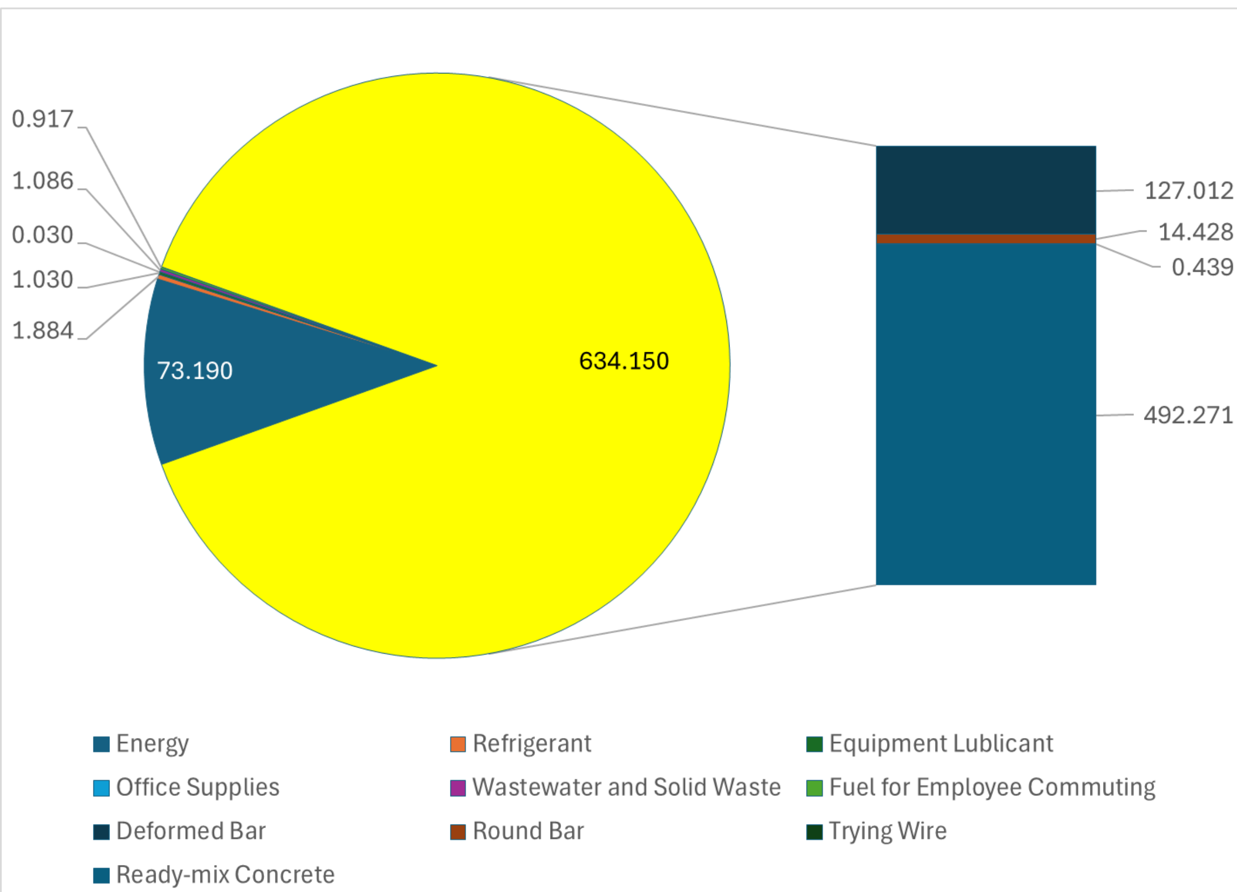

Fig. (3). GHG emissions categorized by resource type.

Table 10. GHG emissions categorized by resource type and emission stages.

Resource	GHG Emission (tCO_2e/Year)				
	Production	Transportation	Construction/ Operation	Waste Disposal	Total
Energy	-	-	-	-	-
Diesel	4.350	0.708	58.470	-	63.526
Gasoline	0.554	0.492	4.974	-	6.208
Electricity	2.886	0.570	-	-	3.456
Total	**7.788**	**1.770**	**63.444**	-	**73.002**
Refrigerant	-	-	-	-	-
R134a	0.052	Unconsidered	0.650	-	0.702
R-22	0.008	Unconsidered	0.061	-	0.069
R-32	0.045	Unconsidered	1.068	-	1.113
Total	**0.105**	-	**1.779**	-	**1.884**
Construction material	-	-	-	-	-
Deformed bar	120.414	6.593	-	0.005	127.012
Round bar	13.277	1.150	-	0.001	14.428
Trying wire	0.329	0.110	-	-	0.439
Ready-mix concrete	485.150	7.121	-	-	492.271
Total	**619.17**	**14.974**	-	**0.006**	**634.150**
Equipment lubricant	-	-	-	-	-
Hydraulic oil	0.577	0.010	-	0.443	1.030
Total	**0.577**	**0.010**	-	**0.443**	**1.030**
Office supplies	-	-	-	-	-
Copier paper	0.012	0.001	-	Unconsidered	0.013
Toilet paper	0.004	0.011	-	0.002	0.017
Total	**0.016**	**0.012**	**0.000**	**0.002**	**0.030**
Wastewater and solid waste	-	-	-	-	-
Water treatment (CH_4)	-	-	1.008	-	1.008
Garbage	-	-	-	0.078	0.078
Total	-	-	**1.008**	**0.078**	**1.086**
Fuel for employee commuting	-	-	-	-	-
Diesel	0.019	0.005	0.253	-	0.277
Gasoline	0.063	0.010	0.567	-	0.640
Total	**0.082**	**0.015**	**0.820**	-	**0.917**
Grand Total	**627.738**	**16.781**	**67.051**	**0.529**	**712.099**

The data in Table **10** and Fig. (**3**) reveal the disproportionate contribution of construction materials, which account for 634.150 tCO_2e (89.05%), far exceeding the emissions from other resource groups. A detailed analysis of resources within this category shows that ready-mix concrete and deformed bars are the primary contributors, generating 492.271 tCO_2e (69.13%) and 127.012 tCO_2e (17.84%), respectively. These results identify these two materials as critical emission hotspots, necessitating focused mitigation efforts.

The primary driver of GHG emissions from construction materials is their volume of usage, which directly correlates with the scope of work and is largely beyond the company's control. However, opportunities exist to reduce emissions by enhancing the efficiency of resource utilization. To assess this, the actual consumption of key construction materials—including ready-mix concrete and reinforcement steel (deformed and round bars)—was compared against the minimum required quantities (or the estimated amounts based on the scope of work, as outlined in the case study).

The analysis revealed utilization ratios of 1.0894 for ready-mix concrete (1,996.50 m^3 used *vs*. 1,832.62 m^3 required) and 1.0930 for reinforcement steel (133,415.12 kg used *vs*. 122,058.04 kg required). This represents an overuse of 8.94% for ready-mix concrete and 9.30% for reinforcement steel. Such findings highlight significant opportunities to improve resource efficiency, particularly for these two key materials.

Based on the findings and discussions in this section, it is evident that optimizing construction processes to improve resource utilization efficiency—particularly concerning ready-mix concrete and reinforcement steel—is a critical strategy for the case study bored pile contractor to control and reduce GHG emissions. The prioritization of environmentally friendly products should also be emphasized. This approach should not be limited to merely selecting conventional concrete from suppliers with lower GHG emissions. Still, it should also encompass the exploration of alternative materials, such as concrete enhanced with various additives. Notable examples include Shredded Waste Paper (SWP) [31], and corncob ash [32-35], both of which contribute to environmental sustainability by reducing waste and minimizing the carbon footprint associated with traditional cement production. Furthermore, using geopolymer fine-grained concrete is recommended, as its manufacturing process has been shown to produce favorable ecological outcomes [36]. In addition, procuring locally sourced materials or those manufactured near project sites should be considered as a strategy to mitigate further GHG emissions associated with transportation.

Furthermore, since the company's carbon footprint (CFO) is primarily attributable to the use of construction materials, which is closely linked to the project scope, the contractor should broaden its perspective beyond merely constructing bored piles according to existing designs and specifications. By developing capabilities to provide design services in collaboration with designers, in the capacity of structural or geotechnical engineers with specialized knowledge in geology and pile design, the company can enhance its value and manage and control its CFO more effectively. This approach improves project and organizational sustainability [37].

Implementing these measures offers a viable pathway for the case study contractor to significantly reduce GHG emissions while fostering long-term sustainability across their operations.

CONCLUSION

This study assessed the organizational carbon footprint of a Thai bored pile contractor for the year 2022. During this period, the company successfully completed 3,454 bored piles with a cumulative drilling volume of 1,998.90 cubic meters. The company also supplied 122,058.04 kilograms of reinforcement steel and 1,832.62 cubic meters of ready-mix concrete.

The analysis determined a total carbon footprint of 712.099 tCO_2e, distributed across three scopes: Scope 1 (direct emissions) accounted for 66.231 tCO_2e (9.30%), Scope 2 (indirect emissions from electricity use) contributed 2.886 tCO_2e (0.41%), and Scope 3 (other indirect emissions) dominated with 642.982 tCO_2e (90.29%). A closer examination of emission sources identified the top three contributors: Scope 3-1 (purchased goods and services), Scope 1-2 (purchased electricity), and Scope 3-4 (upstream transportation and distribution), collectively generating 698.308 tCO_2e or 98.06% of the total emissions.

Further analysis revealed that construction-related activities were the primary contributors to emissions, generating 706.234 tCO_2e (99.18%), while office operations accounted for just 5.865 tCO_2e (0.82%). The emission intensities for key construction activities were 36.06 kg CO_2e per cubic meter for bored pile drilling, 1.16 kg CO_2e per kilogram for reinforcement steel, and 268.62 kg CO_2e per cubic meter for ready-mix concrete. These values provide critical benchmarks for evaluating environmental impacts, developing emission reduction strategies, and guiding sustainability initiatives within the bored pile construction sector. Moreover, they can be applied to embodied carbon assessments for building structures, offering valuable insights for promoting sustainable construction practices.

Total GHG emissions across the four stages—resource production, resource transportation, construction, and waste disposal—amounted to 634.150 tCO_2e (89.05%) from construction materials alone, significantly exceeding emissions from other resource groups. Within this category, ready-mix concrete and deformed bars were the primary contributors, accounting for 492.271 tCO_2e (69.13%) and 127.012 tCO_2e (17.84%), respectively. Considering the material utilization ratios for ready-mix concrete (1.0894) and reinforcement steel (1.0930) in 2022, these findings underscore substantial opportunities to improve resource efficiency for these critical materials.

Findings from this study highlight the urgent need to enhance resource utilization efficiency, particularly for ready-mix concrete and reinforcement steel, in the operations of the case study bored pile contractor. Additionally, adopting environmentally friendly products and prioritizing locally sourced materials can effectively reduce emissions and promote sustainable construction practices. Bored pile contractors in Thailand and worldwide can leverage the emission control and reduction strategies identified in this study to develop tailored approaches for managing and mitigating GHG emissions within their operations. By integrating these strategies, the industry can take meaningful steps toward a more sustainable and low-carbon future.

LIMITATIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

Although the CFO assessment approach employed in this study aligns with established standards, caution is warranted when generalizing these findings to other settings. Variations in construction methodologies and equipment across bored pile contractors can lead to significant differences in emissions profiles. Therefore, when utilizing the CFO data from this case study for benchmarking, it is imperative that evaluators systematically account for operational similarities and differences among organizations to ensure comparability and validity.

Additionally, Emission Factors (EFs) for construction materials vary considerably by country and region. To facilitate accurate comparisons of CFO values or GHG emission data with those from other geographic or international contexts, it may be necessary to adjust the emission factors associated with specific resources or activities. The same consideration applies to the emission intensity data presented in this study: researchers and practitioners should recalibrate emission factors to reflect local or regional conditions adequately.

Although this research represents an early effort to assess the CFO and analyze GHG emission sources within the bored pile contracting sector, it is primarily based on activity and resource usage data collected from a single organization over a specific period. To enhance the robustness and generalizability of future findings, longitudinal studies incorporating multi-year comparisons of GHG emissions are recommended. Such studies would facilitate monitoring temporal changes and trends, enabling continuous evaluation of challenges, intervention strategies, implementation processes, and their effectiveness.

Furthermore, expanding future research to include cross-organizational benchmarking or comparative analyses—either within the bored pile sector or across the broader construction industry—would provide a more comprehensive understanding of GHG emission challenges and promote the identification of best practices. These insights would serve as valuable references for industry practitioners and policymakers, supporting the transition toward a more sustainable and low-carbon construction sector.

Finally, identifying construction materials—particularly concrete and reinforcement steel—as significant hotspots for GHG emissions in this study underscores the urgent need for innovation in these areas. Research focused on developing sustainable alternatives to conventional concrete and reinforcement steel is essential to ensure the long-term sustainability and resilience of the construction industry.

AUTHORS' CONTRIBUTIONS

The authors confirm their contributions to the paper as follows: N.S.: Writing - Original Draft Preparation; N.S., N.B.: Data collection; N.S., S.K., N.B.: Analysis and interpretation of results; N.S., S.K., A.U.: Investigation; S.K., A.U., A.B.: Writing - Reviewing and Editing. All authors reviewed the results and approved the final version of the manuscript.

LIST OF ABBREVIATIONS

CFO	=	Carbon Footprint of Organization
CCF	=	Corporate Carbon Footprint
GHG	=	Greenhouse Gas
SUV	=	Sport Utility Vehicle
BTU	=	British Thermal Unit
TGO	=	Thailand Greenhouse Gas Management Organization
TLCI	=	Thai National Life Cycle Inventory database
B2F	=	Business-to-Customer
EF	=	Emission Factor
SWP	=	Shredded Waste Paper

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

All data generated or analyzed during this study are included in this published article.

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CONFLICT OF INTEREST

The author(s) declare no conflict of interest, financial or otherwise.

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