Journal of Asian Scientific Research
ISSN(e): 2223-1331
ISSN(p): 2226-5724
DOI: 10.55493/5003.v16i2.5935
Vol. 16, No. 2, 113-133.

URL: www.aessweb.com

Assessment of the carbon footprint of football field rental operations in Thailand

Jakkarat Tabwav[1]
Patikorn Sriphirom[2+]
Aungsiri Tipayarom[3]

[1,2,3]*Department of Environmental Science, Faculty of Science, Silpakorn University, Nakhon Pathom 73000, Thailand.*
[1]*Email: daniarm10@icloud.com*
[2]*Email: sriphirom_p@su.ac.th*
[3]*Email: tipayarom_a@su.ac.th*


(+ Corresponding author)

Article History
Received: 29 October 2025
Revised: 30 January 2026
Accepted: 20 February 2026
Published: 10 March 2026

Keywords
Carbon footprint for organization
Environmental footprint
Football field rental business
Greenhouse gas emissions
Thailand.

ABSTRACT

This study is the first to evaluate the greenhouse gas (GHG) emissions associated with football field rental operations in Thailand. The Carbon Footprint for Organization framework, following ISO 14064-1:2018 and the GHG Protocol, was applied to quantify the carbon footprint for both current-year operations (2024) and a 10-year renovation cycle. Two facilities were studied: Field A in Ratchaburi Province (8,000 m^2; natural grass and artificial turf fields) and Field B in Nonthaburi Province (4,800 m^2; two artificial turf fields). GHG emissions were categorized into direct (Scope 1), electricity-related indirect (Scope 2), and other indirect (Scope 3) emissions. In 2024, Scopes 1, 2, and 3 comprised 18.4%, 41.3%, and 40.3% of the total carbon footprint of Field A, and 37.0%, 22.8%, and 40.2% of the total carbon footprint of Field B, respectively. Over the 10-year cycle, renovation activities largely contributed to Scope 3 emissions, increasing total annual carbon footprints by 27.4% for Field A and 19.9% for Field B compared to current operations. Refrigerant leakage, electricity consumption, and employee and customer commuting were the main contributors to Scopes 1, 2, and 3 emissions, respectively. The annual carbon intensity per area ranged from 17.2 to 19.1 kg CO_2eq/m^2 for Field A and 15.2 to 16.4 kg CO_2eq/m^2 for Field B. Field surface type was the major contributor to emission patterns: natural grass fields generated higher operational emissions, whereas artificial turf fields produced greater renovation-related emissions. Using low-carbon electricity, low-carbon or natural refrigerants, and low-embodied-carbon materials may reduce emissions and promote sustainable football field management.

Contribution/ Originality: The paper describes the first assessment of the carbon footprint associated with football field rental operations. It identifies key hotspots for greenhouse gas emissions and proposes practical mitigation strategies aimed at reducing emissions. The goal is to align operational practices with national and global sustainability objectives, promoting environmentally responsible management of sports facilities.

1. INTRODUCTION

Human activities, such as industrial expansion, energy production, transportation, construction, agriculture, livestock farming, and deforestation, contribute to global greenhouse gas (GHG) emissions. Among the major GHGs, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) are the dominant gases driving the greenhouse effect and global warming. This persistent warming influences long-term and often irreversible alterations in the Earth's climatic systems, collectively known as climate change [1]. Mitigating greenhouse gas emissions is considered the most effective strategy for stabilizing the climate system and limiting the increase in average global temperatures.

This approach aligns with the objectives of the Paris Agreement, which aims to keep the global temperature rise well below 2°C above pre-industrial levels [2].

Thailand, as a signatory to the United Nations Framework Convention on Climate Change (UNFCCC) since 1995, has actively pursued national policies to fulfill its international climate commitments [3]. At the 26th Conference of the Parties to the Convention (COP26) held in Glasgow, Scotland, in 2021, Thailand announced ambitious national targets to reduce greenhouse gas emissions. Achieving these goals requires not only accurate measurement of current emissions across all sectors but also effective collaboration among relevant stakeholders. A comprehensive and systematic assessment of greenhouse gas emissions from various activities is essential to ensure the accuracy of the national greenhouse gas inventory, identify emission hotspots, and provide a robust foundation for formulating effective mitigation strategies that support the national emission reduction targets [4].

Football is one of the most popular sports globally and promotes physical fitness, teamwork, and social interaction [5, 6]. Although football-related activities have societal benefits, they also contribute to GHG emissions and have broader environmental impacts throughout their life cycles [7], yet have received relatively limited attention Orr and Inoue [8]. Itten et al. [9] reported that natural grass, artificial turf, and hybrid turf fields exhibit different environmental impacts depending on the construction, maintenance, renovation, and disposal stages. Artificial turf fields, which are composed largely of synthetic materials, produce the highest GHG emissions during construction due to intensive use of material and energy, while disposal of synthetic turf at the end of its lifespan creates additional emissions from waste management processes. In contrast, natural grass fields require constant maintenance, including fertilization and mowing, which contributes significantly to GHG emissions during their operation. The year-round usability and longer lifespan of artificial turf can lower environmental impacts per hour of use compared to natural grass fields. Magnusson and Mácsik [10] concluded that GHG emissions from artificial turf are influenced by material selection, maintenance, and management of dismantled turf. Among granule infills, GHG emissions were highest for thermoplastic elastomers (TPE), followed by ethylene propylene diene monomer (EPDM). The use of recycled infill materials and the reuse of dismantled turf and infill can reduce GHG emissions, highlighting the opportunities for more sustainable artificial turf management.

At the organizational level, Khanna et al. [6] examined the carbon footprint of a football club and found that indirect emissions accounted for over 72% of total GHG emissions, followed by emissions from electricity use, which accounted for approximately 22.5%. In response to growing concerns about these environmental impacts, international organizations such as the Union of European Football Associations (UEFA) and the Fédération Internationale de Football Association (FIFA) have initiated campaigns to promote sustainable and low-carbon practices within the football industry [6].

In Thailand, football field rental businesses have flourished, particularly in urban areas where space is limited, to meet the growing demand for accessible facilities among both recreational players and competitive teams [11]. These facilities typically include a variety of amenities beyond the playing fields themselves, such as cafés, restrooms, fitness centers, and parking spaces [12]. The operation, maintenance, and periodic renovation of these facilities require significant energy, water, and materials, thereby generating both direct and indirect GHG emissions. However, despite their increasing prevalence and resource-intensive nature, football field rental enterprises have received limited scientific attention regarding their environmental impact, particularly concerning GHG emissions.

To address this knowledge gap, this study presents the first carbon footprint assessment of football field rental operations in Thailand using the Carbon Footprint for Organization (CFO) framework. This analysis aimed to answer the following research questions: (1) What are the GHG emissions associated with facility operations during the current-year and a 10-year renovation cycle? (2) How do GHG emissions differ across field materials used? (3) What are the primary sources of GHG emissions? (4) What are the appropriate targeted mitigation strategies?

This paper is structured as follows: Section 2 describes the methodology used in the study. Section 3 presents the empirical findings and discusses the results, including the challenges and opportunities associated with GHG mitigation. Finally, Section 4 summarizes the main conclusions and proposes directions for future research.

2. METHODOLOGY

2.1. Methodological Framework

The carbon footprint assessment for football field rental operations followed the procedural framework shown in Figure 1 and was performed in accordance with internationally recognized standards. These include ISO 14064-1:2018, which provides a standard framework for the quantification and reporting of corporate GHG emissions [13]; the Corporate Accounting and Reporting Standard of the GHG Protocol [14, 15] which establishes fundamental principles for corporate GHG accounting [15] and the Corporate Value Chain Accounting and Reporting Standard (Scope 3) [16] which provides detailed guidance for quantifying and reporting GHG emissions across the value chain [15]. Additional methodological support was drawn from ISO/TR 14069:2013, which supplements ISO 14064-1 by providing practical guidance for implementing corporate GHG accounting [17].

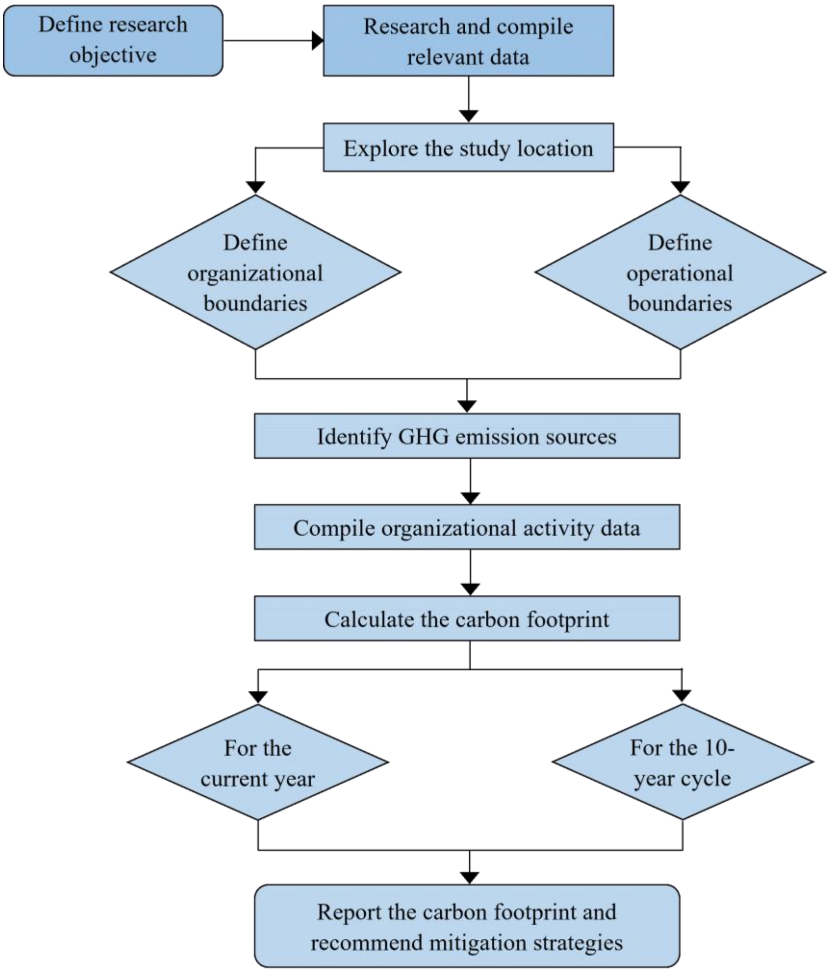

Figure 1. Methodological framework.

This study combined these international frameworks with facility-specific AD obtained from official documents and field audits. Several country-specific and activity-specific EF, as detailed in Section 2.4, were applied. This approach increases the accuracy of the CFO assessment compared to previous studies that relied on estimated AD or questionnaire-based data without direct field investigations and predominantly used global default EF values that may not accurately reflect the geographic context.

2.2. Description of Football Field Rental Operations

This study examined two football field rental facilities, which differed in geographic location, facility characteristics, and field surface type. Field A in Ratchaburi Province covered a total area of approximately 8,000 m^2 (Figure 2a) and comprises two outdoor football fields: a natural grass field (45 × 60 m) and an artificial turf field (50 × 70 m). The facility includes a shop, lounge, and rest area, restroom and shower facilities, an outdoor parking area, and equipment storage and staff rooms. The facility operates from 10:00 to 24:00 (14 hours), with five staff members providing services. Field B in Nonthaburi Province covered a total area of approximately 4,800 m^2 (Figure 2b) and comprises two indoor artificial turf fields, each measuring 20 × 40 m. Additional facilities include a shop and rest area, restroom and shower facilities, indoor and outdoor parking areas, gym rooms, and an equipment storage room. The operation is open daily from 08:30 to 22:00 (9.5 hours), with two staff members on duty. A summary of the key characteristics of both facilities is summarized in Table 1. Overall, both operations are designed to accommodate training, recreational exercise, and competitive events. This reflects the typical operational framework of commercial football field rental businesses in Thailand.

Figure 2. Layouts of football field rental businesses: Field A in Ratchaburi Province (a) and Field B in Nonthaburi Province (b).

Table 1. Components, associated activities, and corresponding GHG emission sources in two football field rental operations.

Components	Sub-components	Related activities	GHG emission sources
Football fields	**Field A**: a natural grass field (2,700 m^2) and an artificial turf field (3,500 m^2) **Field B**: two artificial turf fields (each 800 m^2)	- Use of football fields - Lighting - Field maintenance	- Electricity production and use - Fertilizer production, transportation, and use (Field A only) - Groundwater and tap water use (Field A only) - Fuel oil production and use - Production, transportation, and use of materials for maintenance (details in Table 2)
Shop, lounge, and rest area	**Field A**: a retail shop (volume: 1,200 m^3), lounges (volume: 1,800 m^3), and a rest area (serving approximately 100 persons). **Field B**: a retail shop (volume: 45 m^3) and a rest area (serving approximately 20 persons).	- Use of electrical appliances - Provision of food and beverage services - Waste generation - Air conditioner use	- Electricity production and use - Liquefied petroleum gas (LPG) production and use for small-scale cooking activities - Waste transportation and disposal - Food and beverage production, transportation, and consumption - Air conditioner refrigerant leakage - Tap water production and use - Wastewater management
Restroom and shower facilities	**Field A**: 3 male restrooms, 3 female restrooms, and 3 shower rooms **Field B**: 5 male restrooms, 5 female restrooms, 8 male showers, and 6 female showers	- Tap water use - Restroom use - Wastewater generation - Lighting - Waste generation	- Tap water production and use - Wastewater management - CH_4 emissions from septic tanks - Electricity production and use - Waste transportation and disposal
Parking areas	**Field A**: outdoor parking area (capacity: 15 cars) **Field B**: outdoor parking area (20 cars) and indoor parking area (14 cars)	- Travel of personnel	- Fuel oil production and use - Electricity production and use
Other areas	**Field A**: Equipment storage room (volume: 800 m^3) and staff room (volume: 300 m^3). **Field B**: Gym rooms (volume: 480 m^3) and equipment storage room (volume: 60 m^3).	- Use of electrical appliances - Tap water use - Waste generation - Air conditioner use	- Electricity production and use - Tap water production and use - Waste transportation and disposal - Air conditioner refrigerant leakage - Wastewater management

2.3. Defining Organizational and Operational Boundaries with GHG Emission Sources

The carbon footprint assessment was conducted using the operational control approach at the organizational level. The core activities defining the operational boundaries were categorized into five components: (1) football fields, (2) restroom and shower facilities, (3) shop, lounge, and rest areas, (4) parking areas, and (5) other supporting areas, as summarized in Table 1. The operational boundaries for the carbon footprint assessment were divided into two cases: (1) current-year operations (2024), covering routine operational and maintenance activities, during which Field A operated for 351 days and Field B for 356 days, and (2) a 10-year operational cycle, encompassing both annual routine activities and maintenance or renovation activities aimed at sustaining and improving field quality, assuming that the scope of annual activities and the number of users remain consistent with the 2024 operational year (Table 2).

The sources of GHG emissions associated with each component for routine operations are shown in Table 1 and the emission sources from annual maintenance and the 10-year operational cycle are presented in Table 2. The assessment excluded emissions from the initial construction phase and focused solely on emissions occurring during the operational period, i.e., the current operational year and the 10-year operational cycle, including field renovation activities. Capital goods-related emissions for both facilities were excluded from the carbon footprint assessment in both scenarios.

Table 2. Routine maintenance activities on an annual and 10-year renovation cycle, and GHG emission sources associated with football fields.

Field	Maintenance activity		GHG emission sources	
	Annual maintenance	**10-year renovation cycle**	**Annual maintenance**	**10-year renovation cycle**
A	**Artificial turf field** - Rubber granules are brushed using a grooming machine every 2 months. - EPDM rubber granules are refilled every 6 months at a rate of 20 kg per refill. - Football goal nets, soccer balls, and football pumps are replaced once a year. - Manual labor is employed for the operation. **Natural grass field** - Groundwater is used for irrigation at a rate of 68 m^3 per day. - Tap water is additionally used at a rate of 38.4 m^3 per month - Chemical fertilizers (formulas 46-0-0 and 15-15-15) are applied every 2 months at 10 kg each per application. - Football field boundary lines are painted every 2 months. - Grass is mowed every 2 weeks. - Football goal nets, soccer balls, and football pumps are replaced once a year. - Manual labor is employed for the operation.	**Artificial turf field** - Energy is used by a crane for the demolition process - Replace high-density polyethylene (HDPE) artificial turf sheets (size 4.5 m × 50 m × 5 cm, 16 sheets, 3 kg m^{-2}). - Add fine sand at 23 kg m^{-2}. - Add EPDM rubber granules at 6 kg m^{-2}. - Manual labor is employed for the operation. - Removed turf sheets, rubber granules, and sand are disposed of via municipal landfilling. **Natural grass field** - Replace natural grass sheets (size 0.5 m × 1 m × 1.5 cm, 5,400 sheets, 2 kg per sheet). - Tap water is used at a rate of 3.2 m^3 - Apply fertilizers: 20 kg of formula 46-0-0 and 10 kg of formula 15-15-15. - Add fine sand at 11 kg m^{-2}. - Use one 18-liter bucket of paint for marking field boundaries. - Manual labor is employed for the operation. - Removed grass sheets and sand are disposed of via municipal landfilling.	- Fuel oil production, transportation, and use - EPDM granules production and transportation - Goal nets, soccer balls, and football pumps production and transportation - Electricity production and use - Tap water production and use - Fertilizer production, transportation, and use - Paint production and transportation	- Fuel oil production, transportation, and use - HDPE artificial turf sheets production, transportation, and disposal - Fine sand production, transportation, and disposal - EPDM rubber granules production, transportation, and disposal - Natural grass sheets production, transportation, and disposal - Tap water production and use - Fertilizer production, transportation, and use - Paint production and transportation
B	- Styrene-butadiene rubber (SBR) granules are refilled annually at 12.5 kg per refill per field. - Football goal nets, soccer balls, and football pumps are replaced once a year. - Manual labor is employed to level and smooth the rubber granule surface.	- Energy is used by a crane for the demolition process - Replace HDPE artificial turf sheets (size 3.5 m × 20 m × 5 cm, 12 sheets per field, 3 kg m^{-2}). - Add fine sand at 23 kg m^{-2}. - Add SBR rubber granules at 6 kg m^{-2}. - Manual labor is employed for the operation. - Removed turf sheets, rubber granules, and sand are disposed of via municipal landfilling.	- SBR granules production and transportation - Goal nets, soccer balls, and football pumps production and transportation	- Fuel oil production, transportation, and use - HDPE artificial turf sheets production, transportation, and disposal - Fine sand production, transportation, and disposal - SBR rubber granules production, transportation, and disposal

2.4. Data Collection and Carbon Footprint Calculation

The AD associated with GHG emission sources (Tables 1–2) was primarily derived from existing records, including utility bills, receipts, purchase orders, and field usage and transportation logs. Additional data were collected through on-site surveys about equipment and facilities, such as refrigerators, air conditioners, fire extinguishers, and waste management systems. Key personnel, including field owners, managers, operational staff, housekeeping personnel, and customers, were interviewed and surveyed using questionnaires to address potential data gaps. The focus was on operationally relevant data, excluding personal information. All data and field audits were cross-checked between data collectors, field staff, and facility owners to ensure consistency and accuracy [13, 15-17].

The organizational carbon footprint was calculated by multiplying the activity data (AD) by the emission factor (EF) and the global warming potential (GWP) reported in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) [1, 18, 19]. The EFs used were divided into three levels. Tier 1: global or regional EFs recommended by the IPCC [18, 19], and the Ecoinvent 3.9 database via the SimaPro Craft 10.1 life cycle assessment (LCA) software [20]. Tier 2: national-specific EFs recommended by the Thailand Greenhouse Gas Management Organization (Public Organization; TGO), under the Ministry of Natural Resources and Environment [21, 22]. Tier 3: activity-specific EFs for the relevant producers involved in the football field rental operations, which were verified by the TGO.

According to internationally recognized standards, the organizational carbon footprint is classified into three scopes [16]. Scope 1: direct GHG emissions encompassing emissions directly attributed to the football field rental operations, including mobile combustion associated with business activities, stationary combustion, and fugitive emissions from refrigerants, fertilizer use, and CH_4 from wastewater treatment systems and septic tanks. CH_4 emissions from septic tanks were evaluated based on the number of users across all facilities, while domestic wastewater discharges to aquatic environments (untreated systems) were estimated in accordance with IPCC guidelines [18, 19]. Fire extinguishing agent emissions were excluded, as they were not GHG. Scope 2: indirect GHG emissions from energy refer to indirect emissions associated with the football field rental operation's electricity use, which is purchased from external suppliers. Scope 3: Other indirect GHG emissions include all indirect emissions beyond Scopes 1 and 2 that are attributed to activities related to the operations but not directly owned or controlled by the organization. Scope 3 is divided into 15 categories [16]. In this study, the relevant categories were: (category 1) emissions from the production of goods purchased in the food and beverage services and consumables used for football field operations; (category 3) emissions associated with energy supply accounted for in Scopes 1 and 2; (category 4) emissions from transportation of goods and consumables in category 1; (category 5) emissions from the transportation and disposal of waste produced by the operations; (category 6) emissions from travel undertaken by employees and business owners for operational purposes; and (category 7) emissions from commuting between employees' and customers' residences and the organization. The AD and EF sources used to assess the organizational carbon footprint are shown in Table 3.

Table 3. Sources of AD and EF used to assess the carbon footprint.

GHG activity	Source of activity data	Used EF	
		Tier	Source
Scope 1			
- Fuel oil use for stationary sources (gasoline and LPG) and mobile sources (diesel and gasoline)	- Bills and receipts	1-2	IPCC (Intergovernmental Panel on Climate Change) [18]; IPCC (Intergovernmental Panel on Climate Change) [19] and Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [21]
- Fertilizer use (Field A only)	- Bills and receipts	1	IPCC (Intergovernmental Panel on Climate

GHG activity	Source of activity data	Used EF	
		Tier	Source
			Change) [18] and IPCC (Intergovernmental Panel on Climate Change) [19]
- Air conditioner refrigerant leakage (R-410a (HFC-125 + HFC-32) and HFC-134a for Field A; HCFC-22, HFC-32, and HFC-134a for Field B)	- Bills and receipts	1	IPCC (Intergovernmental Panel on Climate Change) [1]
- Wastewater management (untreated system)	- Recording of users and staff	1	IPCC (Intergovernmental Panel on Climate Change) [18] and IPCC (Intergovernmental Panel on Climate Change) [19]
- CH_4 emissions from septic tanks	- Recording of users and staff	1	IPCC (Intergovernmental Panel on Climate Change) [18] and IPCC (Intergovernmental Panel on Climate Change) [19]
Scope 2			
- Electricity use	- Bills and receipts	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [21]
Scope 3			
Category 1: Purchased goods and services			
- Tap water	- Bills and receipts	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22]
- Drinking water	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [23]
- Soft drinks	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [23]
- Electrolyte drinks	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [23]
- Beer (Field A only)	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization

GHG activity	Source of activity data	Used EF	
		Tier	Source
			(Public Organization) (TGO) [23]
- Snacks	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [23]
- Instant noodles and rice porridge	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [23]
- Garbage bags	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [23]
- Plastic bags	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [23]
- Paint for field boundary lines (Field A only)	- Purchase orders, bills, and receipts	3	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [23]
- Fertilizers (Field A only)	- Purchase orders, bills, and receipts	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22]
- Goal net	- Purchase orders, bills, and receipts	1	Ecoinvent Centre [20]
- Soccer ball	- Purchase orders, bills, and receipts	1	Ecoinvent Centre [20]
- Football pump	- Purchase orders, bills, and receipts	1	Ecoinvent Centre [20]
- EDPM granules (Field A only)	- Purchase orders, bills, and receipts	1	Ecoinvent Centre [20]
- SBR granules (Field B only)	- Purchase orders, bills, and receipts	1	Ecoinvent Centre [20]
Category 3: Fuel and energy-related activities			
- Fuel oil supply	- Bills and receipts	1-2	IPCC (Intergovernmental Panel on Climate Change) [18]; IPCC (Intergovernmental Panel on Climate Change) [19] and Thailand Greenhouse Gas Management

GHG activity	Source of activity data	Used EF	
		Tier	Source
			Organization (Public Organization) (TGO) [21]
- Electricity supply	- Bills and receipts	2	IPCC (Intergovernmental Panel on Climate Change) [18]; IPCC (Intergovernmental Panel on Climate Change) [19] and Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [21]
- LPG supply	- Bills and receipts	1-2	IPCC (Intergovernmental Panel on Climate Change) [18]; IPCC (Intergovernmental Panel on Climate Change) [19] and Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [21]
Category 4: Upstream transportation and distribution			
- Transportation of goods using small 6-wheel truck at 100% loading	- Purchase orders, bills, and receipts - Distance from Google Maps	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22]
- Transportation of goods using small 6-wheel truck at 0% loading	- Purchase orders, bills, and receipts - Distance from Google Maps	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22]
- Transportation of goods using small 4-wheel pickup truck at 100% loading	- Purchase orders, bills, and receipts - Distance from Google Maps	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22]
- Transportation of goods using small 4-wheel pickup truck at 0% loading	- Purchase orders, bills, and receipts - Distance from Google Maps	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22]
Category 5: Waste generated in operations			
- Amount of solid/general waste disposed by municipal landfill	- Interviews - Weighing	2	Thailand Greenhouse Gas Management Organization

GHG activity	Source of activity data	Used EF	
		Tier	Source
			(Public Organization) (TGO) [22]
- Transportation of waste using 6-wheel garbage truck at 100% loading	- Interviews - Distance from Google Maps	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22]
- Transportation of waste using 6-wheel garbage truck at 0% loading	- Interviews - Distance from Google Maps	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22]
Category 6: Business travel			
- Hired transportation for business purposes (vehicle type, fuel type, distance)	- Work orders - Distance from Google Maps - Fuel consumption rate	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22] and Thailand Greenhouse Gas Management Organization [24]
Category 7: Employee and customer commuting			
- Fuel oil consumption for mobile vehicles used by all staff and customers (vehicle type, fuel type, and distance)	- Interviews and questionnaires - Distance from Google Maps - Fuel consumption rate	2	Thailand Greenhouse Gas Management Organization (Public Organization) (TGO) [22] and Thailand Greenhouse Gas Management Organization [24]

2.5. Carbon Footprint Reporting and Carbon Footprint Uncertainty Estimation

Following the carbon footprint calculation, the results are reported for each emission scope in units of carbon dioxide equivalent (CO_2eq) with three significant digits, based on the previously defined operational boundaries. Both football field rental operations were analyzed and compared to determine environmental impacts arising from variations in materials use, operational practices, and energy consumption. To effectively compare operational efficiency and environmental performance, the carbon footprints were normalized per unit area (m^2), per user, and per hour of use, thereby providing standardized carbon intensity metrics. Carbon emission hotspots within the football field rental operations were identified by analyzing the relative contributions of individual activities to total GHG emissions to suggest mitigation strategies.

Since AD collection and EF selection in carbon footprint assessments cannot be performed with absolute precision, the resulting GHG data are associated with uncertainty [24]. The level of uncertainty in the collected data was evaluated using the methodology summarized in Table 4. The overall uncertainty of the carbon footprint was evaluated as the product of the AD and EF uncertainty scores. This methodology allowed the study to classify the quality and reliability of data into three levels: high, moderate, and low uncertainty.

Table 4. Estimation of carbon footprint uncertainty.

Uncertainty estimation	Score	Explanation
AD	3	Data is continuously collected through automated systems, meters, receipts, and official documents.
	2	Data is collected from staff records and site surveys, but lacked confirmation from official documents.
	1	Data is estimated based on assumptions or approximations.
EF	3	EFs from manufacturers or from relevant company-specific Tier 3 sources.
	2	EFs from national-level Tier 2 sources
	1	EFs from regional- or global-level Tier 1 sources
Uncertainty level (uncertainty of AD x EF)	1–3	High uncertainty
	4–6	Moderate uncertainty
	7–9	Low uncertainty

3. RESULTS AND DISCUSSION

3.1. Carbon Footprint of Current-Year Operations

The total GHG emissions of the two football field rental operations across all three scopes in 2024 were 138 tCO_2eq for Field A and 72.8 tCO_2eq for Field B, reflecting the difference in business scale, with Field A being the larger operation. For Field A, GHG emissions from Scope 1, Scope 2, and Scope 3 accounted for 18.4%, 41.3%, and 40.3% of the total, respectively, while Field B's emissions from Scopes 1, 2, and 3 were 37.0%, 22.8%, and 40.2%, respectively (Figure 3).

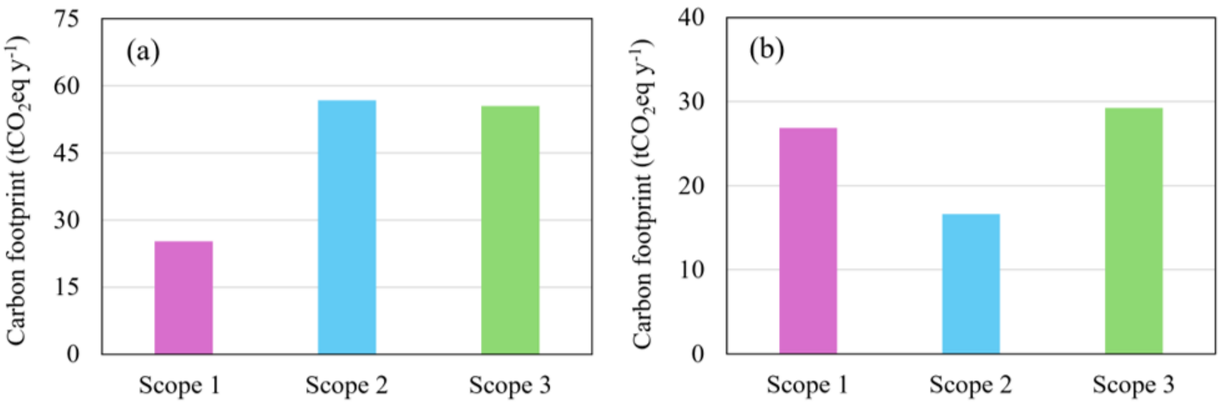

Figure 3. Carbon footprint of current-year operations (2024) across all three scopes in Field A (a) and Field B (b).

The largest contributor to Field A's total carbon footprint was Scope 2 emissions from electricity use, accounting for 56.8 tCO_2eq. In Scope 1, the significant source was refrigerant leakage, primarily from R-410A, which emitted 11.8 tCO_2eq. In Scope 3, the major contributor was employee and customer commuting (category 7), contributing 25.1 tCO_2eq. For Field B, Scope 3 emissions were the most substantial, totaling 29.3 tCO_2eq, primarily attributable to employee and customer commuting (category 7). Scopes 1 and 2 contributed less, with refrigerant leaks (mainly HCFC-22) identified as the primary Scope 1 source, emitting 19.9 tCO_2eq. The overall distribution of GHG emission sources is illustrated in Figure 4.

The carbon footprint from refrigerant leaks in Scope 1 for both operations is attributed to the routine operation of air conditioners, with the leaked refrigerants having high GWP [1]. The larger scale of Field A also resulted in higher emissions from septic tanks and wastewater treatment, as CH_4 emissions from wastewater depend on the population served [18, 19]. Fuel combustion contributed minimally to total emissions because of the limited use of fuels. Field A's higher electricity consumption was primarily required to provide lighting and safety measures throughout the larger facility, particularly in outdoor areas. Khanna et al. [6] and Karaman and Özsoy [25] also reported that energy consumption is a key contributor to carbon-based emissions from European football clubs.

A similar pattern was observed in Scope 3, where employee and customer commuting were the largest emission sources, reflecting the travel required to access services. This finding is consistent with Khanna et al. [6], who reported that supporter travel was the largest contributor to Scope 3 emissions in football club operations, and also noted that this source is difficult to mitigate because of its association with external stakeholders. Herold et al. [26] reported that spectator travel to home professional football matches in Austria, primarily using personal vehicles, contributed to 71.6% of total GHG emissions.

Pereira et al. [27] also concluded that transportation was a major contributor to the carbon footprint of English Premier League clubs, accounting for 61% of total GHG emissions. Therefore, reducing the frequency or volume of travel represents a primary mitigation strategy. The second-largest source in Scope 3 was emissions from the manufacture of goods purchased for food and beverage services and consumables used in football field operations (category 1).

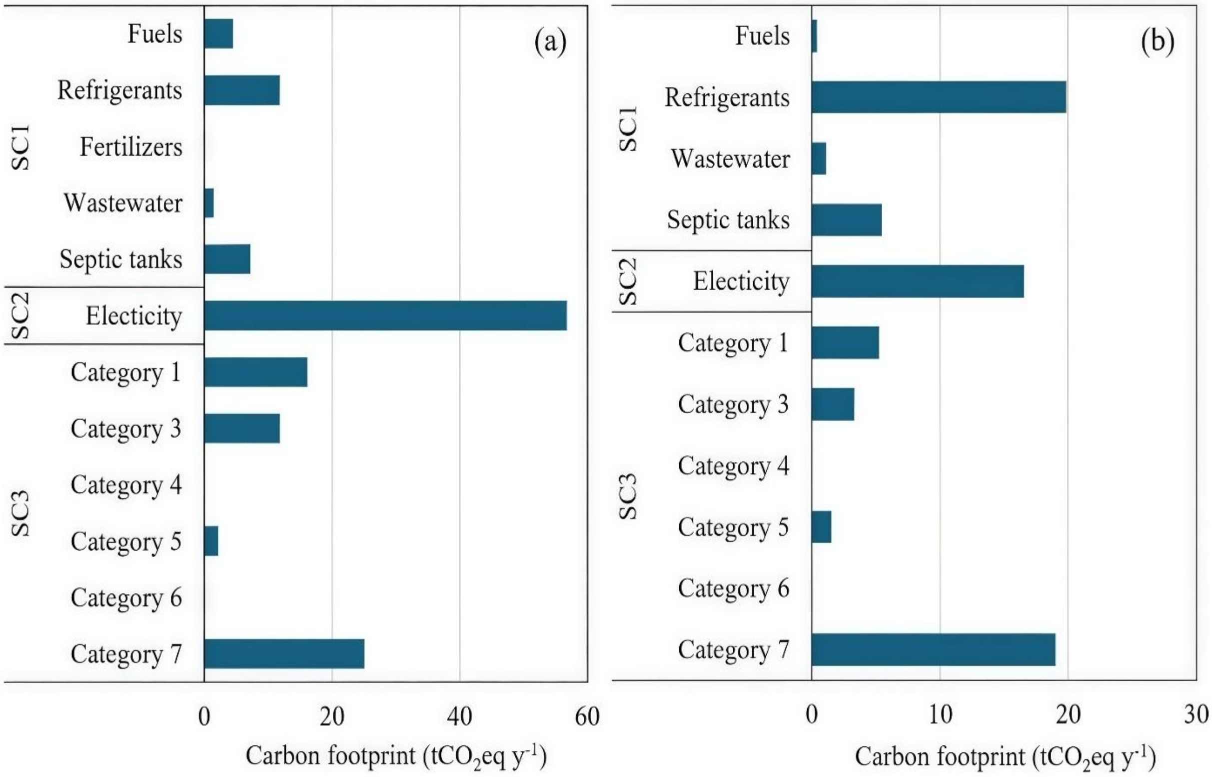

Figure 4. Carbon footprint of current-year operations (2024) for each activity in Field A (a) and Field B (b). SC1, SC2, and SC3 represent Scope 1, Scope 2, and Scope 3 emissions, respectively.

When the annual carbon footprint intensities for current-year operations were normalized per unit area, user, and hour of use, the current-year carbon footprint ranged from 15.2 to 17.2 kgCO_2eq m^{-2}, 2.26 to 3.32 kgCO_2eq user^{-1}, and 21.5 to 28.0 kgCO_2eq h^{-1} of use (Table 5). Field A consistently exhibited a higher normalized total carbon footprint than Field B by 13.4%, 47.2%, and 30.1% per m^2, per user, and per hour, respectively, primarily due to larger operational areas and associated electricity use for safety. For Scope 2, the normalized carbon footprint of Field A exceeded that of Field B by 105%, 166%, and 136% per m^2, user, and hour, respectively. Conversely, for Scope 1, Field B contributed 77.5%, 36.8%, and 54.8% more than Field A per m^2, user, and hour, respectively, largely because of the high GWP of the refrigerants used in the air conditioning systems.

Table 5. Annual carbon footprint intensity for current-year operations and 10-year operational cycle, normalized per unit area, per user, and per hour of use.

Field	Scope	Carbon intensity ($kgCO_2eq$)					
		Per square meter (m^{-2})		Per user ($user^{-1}$)		Per hour of use (h^{-1})	
		Current year	10-year cycle	Current year	10-year cycle	Current year	10-year cycle
A	1	3.16	3.16	0.61	0.61	5.14	5.14
	2	7.10	7.10	1.37	1.37	11.6	11.6
	3	6.94	8.84	1.34	1.71	11.3	14.4
	Total	17.2	19.1	3.32	3.69	28.0	31.1
B	1	5.60	5.60	0.83	0.83	7.95	7.95
	2	3.46	3.46	0.51	0.51	4.91	4.91
	3	6.10	7.31	0.91	1.09	8.65	10.4
	Total	15.2	16.4	2.26	2.44	21.5	23.2

Itten et al. [9] revealed that GHG emissions per hour of use of natural and artificial turf fields, estimated using the LCA method, ranged from 35 to 52 $kgCO_2eq$, which is higher than the results of this study. This difference can be explained by the fact that this study did not take into account GHG emissions during the construction phase. Itten et al. [9] reported that the carbon footprint during this stage was less than 15 $kgCO_2eq$ (average: 11 $kgCO_2eq$). Combining this value with the results of the present study yields a range of 32.5–39.0 $kgCO_2eq$, which is consistent with that of Itten et al. [9]. The reduced GHG emissions observed in this study are likely due to the use of manual labor in some maintenance processes, unlike the mechanization used in Itten et al. [9].

3.2. Annual Carbon Footprint of the 10-Year Operational Cycle

Because football field rental operations do not sustain uniform activity levels each year, major renovation activities are typically performed approximately once every 10 years. The 10-year carbon footprint was estimated in conjunction with the current-year operations to more accurately reflect actual annual GHG emissions. As illustrated in Figure 5, Scope 1 and 2 emissions remained relatively constant throughout the cycle, with the exception of Field A, which features a natural grass surface requiring fertilization during renovation. In contrast, renovation activities primarily contributed to Scope 3 emissions, particularly from categories 1, 4, and 5, as summarized in Table 2. Compared to current-year operations, Scope 3 emissions increased by 27.4% for Field A and 19.9% for Field B. Overall, renovation activities contributed approximately 15.2 and 5.81 tCO_2eq per year for Field A and Field B, respectively. These results indicate that Figure 5 provides a more representative estimate of the average annual carbon footprint than the current-year data shown in Figure 3.

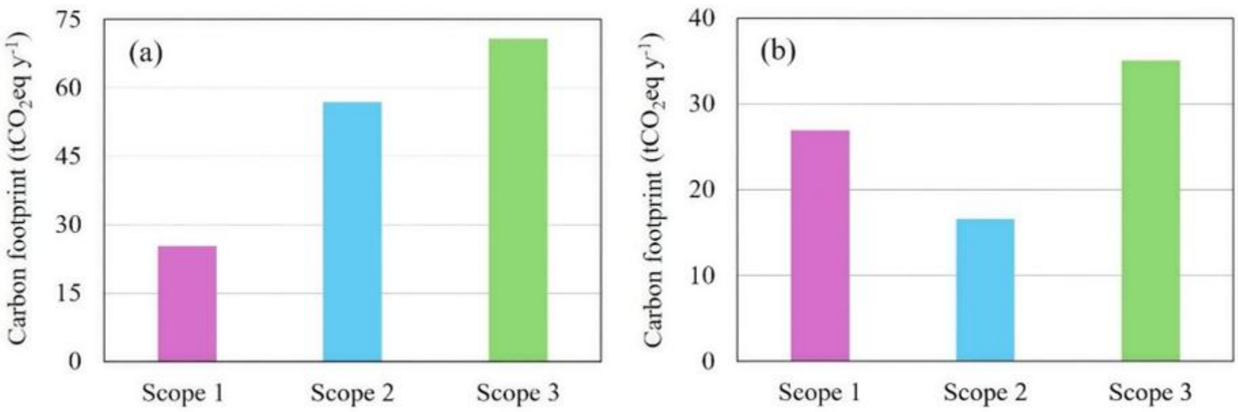

Figure 5. Annual carbon footprint of 10-year football field rental operations for Field A (a) and Field B (b).

When expressed as the annual carbon intensity (Table 5), the values were in the range of 16.4–19.1 $kgCO_2eq\ m^{-2}$, 2.44–3.69 $kgCO_2eq\ user^{-1}$, and 23.2–31.1 $kgCO_2eq\ h^{-1}$ of use. The overall trends were comparable to those observed in the current year, except for Scope 3, which revealed a pronounced increase. The annual carbon intensity of Scope 3 emissions for Field A exceeded that of Field B by 20.9%, 57.0%, and 38.7% when expressed per m^2, per user, and per hour of use, respectively, representing an increase of 7.14–9.26% relative to the current-year differences between the two operations. This pattern suggests that Field A consistently consumes more quantities of materials and consumables during renovation, even after normalizing by area, user, or operational time. Therefore, when evaluated based on annual carbon intensity, Field A's football field rental operations impose a higher environmental burden in terms of GHG emissions than Field B. In particular, renovation activities emerge as a critical carbon footprint hotspot, highlighting the need for targeted mitigation strategies in operational planning. This point is supported by Itten et al. [9], who showed that the use of higher volumes of materials for both natural and artificial turf fields significantly contributes to higher GHG emissions. Green procurement, such as utilizing low-carbon materials and consumables, should be implemented to reduce the GHG emissions associated with this aspect [28].

3.3. Comparison of Carbon Footprints Across Football Fields with Different Surface Materials

The observed differences in carbon footprints between the two football field rental operations largely resulted from variations in the type of field surface and materials used. To enable a fair comparison of environmental impacts, the carbon footprint was presented on a per m^2 basis, accounting for both routine maintenance and major renovation activities (Table 3). This estimation excludes emissions from the manufacture and transportation of soccer balls, football goal nets, and pumps. Football fields constructed with different surface materials revealed distinct carbon footprints (Table 6). During annual maintenance, the natural grass field generated significantly higher GHG emissions than both indoor and outdoor artificial turf fields. This was primarily attributed to fuel consumption for lawn mowing and turf rolling, as well as fertilizer and tap water usage. Conversely, the carbon footprint did not differ significantly between indoor and outdoor artificial turf fields during routine maintenance.

In contrast, during the 10-year renovation cycle, artificial turf fields demonstrated considerably higher GHG emissions than natural grass fields, ranging from 36.3–40.8 $kgCO_2eq\ m^{-2}$ for artificial turf fields and 3.39 $kgCO_2eq\ m^{-2}$ for natural grass fields. This discrepancy was largely due to the high GHG emissions associated with the production of HDPE artificial turf sheets and synthetic rubber granules, as well as the transportation and disposal of refurbishment waste. Differences between indoor and outdoor artificial turf fields were attributable to the type of rubber granules used. Outdoor fields used EPDM rubber granules, which have a higher emission factor (EF) than SBR rubber granules employed in indoor fields.

Table 6. Carbon footprint from current-year maintenance and 10-year renovation activities of football fields with different surface materials.

Football field type	Carbon footprint ($kgCO_2eq\ m^{-2}$)	
	Current-year maintenance	10-year renovation activity
Outdoor natural grass field (Field A)	0.44	3.39
Outdoor artificial turf field (Field A)	0.03	40.8
Indoor artificial turf field (Field B)	0.02	36.3

These findings are consistent with Itten et al. [9], who reported that the construction, renovation, and disposal phases of natural grass fields generate lower GHG emissions than those associated with artificial turf fields. In contrast, during the maintenance phase, fertilizer and fuel use on natural grass fields contributes higher GHG emissions compared to artificial turf systems.

3.4. Uncertainty Assessment of Carbon Footprint Data

Although this study expanded considerably in gathering data based on reliable evidence, field surveys, and structured interviews, some uncertainty remains in the obtained carbon footprint data. Most AD values were derived from bills, receipts, purchase records, and field audits, partially supplemented with assumptions or approximations.

Additionally, EFs were primarily based on all levels, resulting in moderate uncertainty across Scopes 1–3. For Scope 3, category 7 (and some items in categories 1 and 3) exhibited relatively high uncertainty because of the indirect nature of data collection and the use of EFs from Tier 1. In contrast, the other categories were assessed as having low to moderate uncertainty levels, as AD were obtained from reliable documents and the EFs were derived from Tier 2–3 sources (Table 7).

Despite moderate uncertainty in most components, the carbon footprint estimates adhered to widely accepted standard methodologies. This aligns with other carbon footprint studies [6, 25-27, 29], which obtained activity data from interviews, questionnaires, or literature reviews and utilized emission factor (EF) values from life cycle assessment (LCA) software databases. To enhance the validity and reliability of future assessments, systematic and continuous data collection is recommended, along with the development and application of site- and activity-specific emission factors [19].

Table 7. Level of uncertainty in carbon footprint data by scope.

GHG activity	Uncertainty level
Scope 1 (Fuels, fertilizers, refrigerant leakage, septic tanks, and wastewater management)	Moderate–High
Scope 2 (Electricity consumption)	Moderate
Scope 3	
Category 1: Purchased goods and services	Low–High
Category 3: Fuel and energy-related activities	Moderate–High
Category 4: Upstream transportation and distribution	Moderate
Category 5: Waste generated in operations	Moderate
Category 6: Business travel	Moderate
Category 7: Employee and customer commuting	High

3.5. Mitigation Strategy Recommendations for Football Field Rental Operations

This study indicates that football field rental operations contribute significant GHG emissions, with the maintenance and renovation of natural grass and artificial turf fields emerging as major emission hotspots. Consequently, targeted mitigation strategies are necessary to reduce the environmental footprint of these businesses, and these are described below.

3.5.1. Addressing Major Sources of Carbon Footprint

Electricity consumption and refrigerant leakage were identified as the primary contributors to GHG emissions, highlighting the need for transitions to cleaner energy sources and refrigerants.

Electricity remains a dominant source of carbon emissions, accounting for 41.3% and 22.8% of the total carbon footprint for Fields A and B, respectively. The adoption of renewable energy, particularly photovoltaic (PV) solar systems, is recommended to partially or fully offset operational electricity demand. De Souza et al. [30] showed that PV solar energy could reduce GHG emissions by approximately 207.88 $kgCO_2eq\ y^{-1}$ relative to grid electricity. However, cost-effectiveness and suitability are important considerations for small- and medium-sized enterprises (SMEs). Peffley and Pearce [31] reported that hybrid systems combining solar PV, batteries, and generators are technically feasible for SMEs, especially when supported by government-sponsored programs. Atchike et al. [32] found that economic incentives significantly influenced the adoption of solar energy, while Mehedi et al. [33] estimated an average energy payback period of 3.8 years (range: 3.3–4.2 years). Based on owner interviews in this study, entrepreneurs are interested in solar power installation to reduce both electricity costs and the carbon footprint, especially given the availability of rooftop and ground areas suitable for installation, and potential access to subsidies. Domański [29] proposed that the deployment of PV systems is a key technology to achieve complete carbon neutrality. GHG emissions from refrigerant leaks constitute a significant source of Scope 1 emissions. Transitioning to refrigerants with lower GWP should be undertaken, especially during air conditioner replacement.

Abas et al. [34] identified environmentally friendly natural refrigerants (CO_2, NH_3, and HCs) and synthetic alternatives (R-152a and R-1234yf) as the optimal options to reduce climate impact.

3.5.2. Sustainable Management of Artificial Turf Fields

Maintenance and improvement of artificial turf fields have been identified as the major contributors to Scope 3 emissions (Figure 5), primarily due to the production and disposal of HDPE turf sheets and synthetic rubber granules.

Using recycled or lower-emission materials, such as recycled EPDM, SBR, TPE, or natural cork, as the rubber granule infill can reduce GHG emissions. Magnusson and Mácsik [10] suggested that the reuse of synthetic infills, soil, and removed turf decreases energy use and GHG emissions. Russo et al. [35] emphasized that recycling synthetic rubber granules is important for sustainability. However, synthetic infills may release microplastics and harmful substances, such as polycyclic aromatic hydrocarbons, which require careful management [7, 36]. Other options include repurposing used rubber granules for construction, road reinforcement, paving, or soundproofing applications [36]. Indoor fields may use natural cork infills, which have low environmental harmfulness and offer a negative carbon balance (–72.5 $kgCO_2eq\ kg^{-1}$) [37]. FIFA and UEFA also promote the use of organic infill materials, such as wood or coconut shells [6]. In addition to reducing the carbon footprint, football field management should prioritize player safety in line with international standards [38]. Hybrid turf systems integrate synthetic reinforcement fibers into natural grass rather than implementing fully synthetic carpets. This approach reduces the embodied carbon and microplastic emissions associated with the polymer manufacturing process, resulting in a lower carbon footprint per hour of use [9]. Recycling of synthetic turf components, including polyethylene and polypropylene fibers, backing materials, and shock pads, recovers high-value polymers for secondary use. Mechanical recycling techniques (shredding, separation, and granulation) produce recycled material for new artificial turf systems or the manufacture of other plastics. LCA studies have shown that recycling artificial turf can reduce overall GHG emissions by 30–50% compared to landfilling or energy recovery [9]. Recycled rubber granules can also be reused for playgrounds, athletic tracks, or molded products [10]. Systematic recycling programs for turf and infill materials, supported by traceable collection systems and policy frameworks, are essential for maximizing GHG emissions reductions and promoting circular economy management [7].

3.5.3. Optimization of Natural Grass Field Maintenance

Regular maintenance of natural grass fields contributes significantly to GHG emissions through fertilizer application, water use, and fuel used for mowing and turf rolling.

Fertilizer use accounts for over 20% of the Scope 1 carbon footprint. Fertilizer application based on soil nutrient analysis can prevent over-application and decrease both direct and indirect N_2O emissions Rees et al. [39]. Hassan et al. [40] reported that adjusting nitrogen supply to crop demand reduces soil nitrogen residuals and associated N_2O emissions. Similarly, Cui et al. [41] showed that optimized nitrogen application constitutes a crucial mitigation strategy, accounting for 86% of the emissions reductions while maintaining crop yields.

Transitioning to electric or hybrid lawnmowers and turf rollers powered by renewable energy can reduce operational GHG emissions, especially when older machinery reaches the end-of-life stage. The use of soil moisture sensors and controllable irrigation schedules can reduce water use without compromising turf quality. Subsurface drainage layers control water movement, prevent waterlogging, and maintain optimal soil moisture levels, which decreases tap water use and associated GHG emissions Itten et al. [9]. Russo et al. [35] recommend combining water-saving technologies with low-maintenance turfgrass varieties to mitigate environmental impacts.

3.5.4. Integrated Operational Planning and Stakeholder Engagement

A holistic approach combining hotspot management, sustainable material selection, and life-cycle management can maximize GHG emissions reductions. Annual carbon footprint tracking enables operators to identify hotspots and assess the effectiveness of mitigation efforts. Collaboration with local authorities, suppliers, sustainability organizations (e.g., TGO), and customers is crucial for implementing low-carbon field management. Incentives for adopting energy-efficient technologies and sustainable materials further augment environmental performance. Encouraging group travel among customers through green travel campaigns or the use of lower-emission vehicles represents another essential approach to reducing indirect GHG emissions [26, 27]. Ultimately, success requires the cooperation of all stakeholders in promoting sustainable recreational sports infrastructure to avoid achieving carbon neutrality through greenwashing strategies, as reported by Karaman and Özsoy [25]. The above discussion is in line with Ardali et al. [28], who emphasized that optimizing energy and water use, implementing green management practices, using renewable energy, and promoting education are all important strategies for mitigating GHG emissions in football. Cooperation among clubs, coaches, athletes, fans, and institutions (e.g., FIFA, continental federations) with international bodies such as the United Nations should be implemented to effectively reduce GHG emissions.

4. CONCLUSIONS

The annual carbon footprint associated with Scopes 1–3 of the football field rental operations during the current year was estimated to be 138 tCO_2eq (17.2 $kgCO_2eq\ m^{-2}$) for Field A in Ratchaburi Province and 72.8 tCO_2eq (15.2 $kgCO_2eq\ m^{-2}$) for Field B in Nonthaburi Province. In Scopes 1–2, electrical power consumption was the primary contributor to emissions in the larger facility, whereas refrigerant leakage associated with high GWP gases was the dominant source in the smaller facility. Under Scope 3, employee and customer travel accounted for the highest share of emissions among all categories. Over a 10-year operational cycle, the total annualized carbon footprint was estimated to be 153 tCO_2eq (19.1 $kgCO_2eq\ m^{-2}$) for Field A and 120 tCO_2eq (16.4 $kgCO_2eq\ m^{-2}$) for Field B. The majority of these emissions originated from Scope 3, particularly categories 1 and 5, which relate to the manufacture of renovation materials and the disposal of renovation waste, respectively. Carbon intensity analysis indicated that the natural grass field exhibited a significantly higher carbon footprint during routine annual maintenance, primarily because of fuel use, fertilizer application, and tap water use. In contrast, the artificial turf field exhibited higher carbon footprints over the 10-year renovation cycle, primarily driven by the production and disposal of HDPE turf sheets and synthetic rubber granules. To mitigate GHG emissions, potential strategies include transitioning to low-carbon electricity sources, using natural or low-GWP refrigerants, and opting for low-carbon rubber infills and turf materials, such as recycled, natural, or hybrid rubber infill systems. Additional approaches include recycling synthetic turf components, using precision fertilization, employing energy-efficient machinery, implementing water-efficient irrigation and drainage systems, and promoting stakeholder engagement to enhance the sustainability of recreational sports infrastructure. Further research should be performed to assess the carbon footprint reductions resulting from the implementation of mitigation technologies to strengthen incentives for business owners and identify the optimal means to mitigate GHG emissions through integrated operations of all stakeholders across the football industry supply chain and other sport sectors.

Funding: This study received no specific financial support.
Institutional Review Board Statement: This research was reviewed and deemed exempt by the Silpakorn University, Thailand IRB under category 2, as it involved minimal risk and the use of anonymous data.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: Research design, methodology, empirical analysis, writing—original draft, and writing—review & editing, Jakkarat Tabwav (J.T.) and Patikorn Sriphirom (P.S.); writing—review & editing, Aungsiri Tipayarom (A.T.). All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.
Disclosure of AI Use: The authors used OpenAI's ChatGPT (version October 2025) to improve the grammar of the manuscript. All content was reviewed and verified by the authors.

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