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Carbon Footprint Assessment of an Industrial Technical College in Misurata – Libya, Using the GHG Protocol (Scope 1 & 2)

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Index Terms

Carbon footprint; Higher education institution; Scope 1 and 2 emissions; Energy consumption; Carbon management.

Abstract

This study presents an operational carbon footprint assessment of the Industrial Technical College in Libya, focusing on Scope 1 and Scope 2 greenhouse gas emissions. Activity data were collected for electricity consumption, diesel fuel use in backup generators, gasoline use for college-owned vehicles, and estimated refrigerant fugitive emissions, with annual totals for 2025 serving as the basis for calculations. Emissions were quantified using internationally recognized methodologies, including the GHG Protocol and IPCC guidelines.

The total annual carbon footprint was estimated at approximately 363.32 tCO_2e, with purchased electricity accounting for approximately 91.8% of the total. Estimated refrigerant fugitive emissions were included as an additional Scope 1 source and represented about 3.7% of total emissions, while institution-owned vehicles and diesel generators contributed approximately 2.8% and 1.6%, respectively.

The study identifies electricity consumption as the primary emission hotspot and proposes targeted mitigation strategies, including renewable energy integration, energy efficiency improvements, and optimized transportation practices. The findings provide a robust baseline for institutional sustainability planning and emphasize the importance of carbon management in higher education settings, offering guidance for similar colleges and universities in Libya and other developing regions.

تقييم البصمة الكربونية لكلية التقنية الصناعية في مصراتة – ليبيا، باستخدام بروتوكول غازات الاحتباس الحراري (النطاق 1 و2)

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الكلمات المفتاحية

البصمة الكربونية، مؤسسات التعليم العالي، انبعاثات النطاق الأول والثاني، استهلاك الطاقة، إدارة الكربون.

الملخص

تقدم هذه الدراسة تقييمًا تشغيليًا للبصمة الكربونية للكلية التقنية الصناعية في ليبيا، مع التركيز على انبعاثات غازات الاحتباس الحراري من النطاقين 1 و2، تم جمع بيانات النشاط لاستهلاك الكهرباء، واستخدام وقود الديزل في المولدات الاحتياطية، واستخدام البنزين للمركبات المملوكة للكلية، وانبعاثات غاز التبريد المتسربة المقدرة، مع اعتبار الإجماليات السنوية لعام 2025 أساسًا للحسابات. حُددت الانبعاثات كميًا باستخدام منهجيات معترف بها دوليًا، بما في ذلك بروتوكول غازات الاحتباس الحراري وإرشادات الهيئة الحكومية الدولية المعنية بتغير المناخ.

قُدِّر إجمالي البصمة الكربونية السنوية بحوالي 363.32 طن من مكافئ ثاني أكسيد الكربون، حيث مثّلت الكهرباء المشتراة حوالي 91.8% من الإجمالي. وأُضيفت انبعاثات غازات التبريد المتسربة كمصدر إضافي ضمن النطاق 1، ومثّلت حوالي 3.7% من إجمالي الانبعاثات، بينما ساهمت المركبات المملوكة للمؤسسة ومولدات الديزل بحوالي 2.8% و1.6% على التوالي.

تُحدد الدراسة استهلاك الكهرباء باعتباره المصدر الرئيسي للانبعاثات، وتقترح استراتيجيات تخفيف مُستهدفة، تشمل دمج الطاقة المتجددة، وتحسين كفاءة الطاقة، وممارسات النقل المُحسّنة. توفر النتائج أساسًا قويًا لتخطيط الاستدامة المؤسسية وتؤكد على أهمية إدارة الكربون في مؤسسات التعليم العالي، وتقدم إرشادات للكليات والجامعات المماثلة في ليبيا والمناطق النامية الأخرى.

I. INTRODUCTION

Higher education institutions play a vital role in advancing sustainable development, not only through education and research, but also through their operational activities [1]. Universities and technical colleges operate as complex systems that include classrooms, laboratories, workshops, and administrative facilities, which require continuous energy and resource consumption and consequently contribute to greenhouse gas (GHG) emissions if sustainability measures are not adequately addressed [2].

In response to increasing global concern over climate change, carbon footprint assessment has become a widely adopted approach for evaluating environmental performance in higher education institutions [3]. A carbon footprint represents the total amount of greenhouse gas emissions expressed in carbon dioxide equivalent (CO_2e), providing a quantitative basis for identifying emission sources, supporting mitigation strategies, and guiding sustainability-related decision-making [4].

Technical and industrial colleges exhibit operational characteristics that differ from those of traditional academic institutions due to the diversity of their educational and training activities. However, despite their important role in applied education and skills development, carbon footprint assessments focusing specifically on technical and industrial education institutions remain relatively limited, particularly in developing regions [5].

Accordingly, this study aims to calculate and analyze the carbon footprint of the Industrial Technical College using internationally recognized carbon accounting methodologies. The findings are expected to support institutional sustainability planning and contribute empirical evidence to the growing literature on carbon footprint assessment in higher education institutions [6].

Recent studies have demonstrated the effectiveness of standardized methodologies such as the GHG Protocol and IPCC emission factor approaches in quantifying carbon footprints of higher education institutions (Aquino et al., 2024) [7]. These studies consistently identify electricity consumption and purchased thermal energy as the dominant contributors to total emissions, often accounting for more than half of institutional carbon footprints (Tirink et al., 2023) [8].

Research focusing on universities in Asia and Europe reported that emission trends are closely linked to campus expansion, increased building floor area, and growing operational demand (Canencio et al., 2024) [9]. Such findings highlight the importance of integrating carbon management into institutional planning processes.

Several studies employing Life Cycle Assessment (LCA) techniques revealed that technical and engineering-oriented institutions generate higher emissions due to laboratories, workshops, and specialized equipment (Guvenc et al., 2023) [10]. These results emphasize the need for customized mitigation strategies tailored to the characteristics of technical colleges rather than generic university-wide solutions.

In addition to energy-related emissions, other studies highlighted the growing importance of Scope 3 emissions, particularly those associated with water consumption, waste generation, paper use, and daily activities of students and staff (Misni et al., 2019) [11]. These findings indicate that indirect emissions, although often underestimated, can represent a non-negligible share of institutional carbon footprints and should be incorporated into comprehensive carbon accounting frameworks.

More recent investigations have explored pathways toward carbon neutrality in higher education institutions, demonstrating that integrating renewable energy systems - particularly solar photovoltaic technologies - combined with energy efficiency measures can reduce institutional carbon footprints by more than 30% (Deda et al., 2025) [12]. These studies stress the importance of reliable data collection, long-term planning, and institutional commitment to sustainability transitions.

Furthermore, studies focusing on specialized academic institutions, such as medical and health-related colleges, revealed that laboratories and research facilities significantly influence overall emission levels (Roknaldin et al., 2024) [13]. Data availability and quality were identified as key challenges, emphasizing the need for structured data management systems to improve the accuracy of carbon footprint assessments.

Despite these advances, the literature indicates a lack of detailed carbon footprint assessments for industrial and technical colleges, especially in developing regions (Lin et al., 2024) [14]..

II. METHODOLOGY

This study adopts a structured and systematic approach to assess the carbon footprint of the Industrial Technical College. In alignment with data availability and institutional boundaries, the assessment focuses exclusively on Scope 1 and Scope 2 emissions, as defined by the GHG Protocol. Scope 1 includes direct emissions from diesel fuel consumption in backup generators, fuel use by institution-owned vehicles, and fugitive refrigerant emissions from air-conditioning and refrigeration equipment, while Scope 2 accounts for indirect emissions resulting from purchased electricity. Scope 3 emissions are excluded from the present analysis to ensure data reliability and methodological consistency.

The carbon footprint assessment is conducted through a sequence of well-defined steps designed to ensure transparency, reproducibility, and alignment with international carbon accounting practices. These steps include:

i. setting the assessment goal.
ii. mapping carbon emission sources.
iii. setting emission-related targets.
iv. identifying and engaging relevant stakeholders.

A. Assessment Framework

1) Goal definition

The primary goal of this study is to quantify the carbon footprint of the Industrial Technical College by calculating greenhouse gas emissions associated with Scope 1 and Scope 2 activities. The results aim to identify major emission sources within the institution and provide a scientific basis for sustainability planning and future mitigation strategies.

2) Identifying carbon emission sources

All relevant emission sources within the institution's boundaries were identified and categorized into two groups: Scope 1 and Scope 2. Sources in Scope 1 include on-site fuel consumption for generator operation, emissions from institution-owned vehicles, and gases leaking from refrigeration and air conditioning systems, while Scope 2 sources relate to purchased electricity consumed by academic, administrative, and service buildings within the college.

3) Target setting

Based on the baseline carbon footprint findings of this study, emissions reduction targets will be set to support corporate sustainability goals. These targets will serve as benchmarks for evaluating potential mitigation measures and monitoring future performance improvements.

4) Stakeholder mapping

Key stakeholders involved in or affected by carbon-related activities were identified. These include facility management personnel, administrative staff, transportation unit representatives, and academic departments. Stakeholder mapping supports data collection, enhances result accuracy, and facilitates the practical implementation of emission reduction strategies.

B. Data Collection

In accordance with the GHG Protocol Corporate Accounting and Reporting Standard, the organizational boundary of this study was defined using the Operational Control Approach. Accordingly, the inventory includes only facilities and activities under the direct operational control of the Industrial Technical College, namely the main academic and administrative campus buildings, backup generators, and institution-owned vehicles. Facilities associated with the college but operated under separate administrative and operational structures, such as the hotel and on-campus staff residential housing, were excluded from the assessment. This boundary definition ensures consistency between operational responsibility, data ownership, and Scope 1 and Scope 2 emission reporting.

1) Scope 3 Screening and Exclusion

Although the present study focuses on Scope 1 and Scope 2 emissions, major potential Scope 3 categories relevant to higher education institutions were screened qualitatively. These categories include student and staff commuting, business travel for academic and administrative purposes, paper consumption, water use, solid waste generation, and purchased goods and services. However, these categories were not quantified in the present inventory due to the absence of complete, verifiable, and consistently recorded activity data for the 2025 reporting year.

Therefore, Scope 3 emissions were excluded from the quantitative assessment to maintain data reliability and methodological consistency. This exclusion is acknowledged as a limitation of the study. Future carbon inventories of the college should prioritize the systematic collection of Scope 3 activity data, particularly for commuting, waste, paper consumption, and academic travel, to support a more comprehensive institutional carbon footprint assessment.

Data were collected for the following emission sources:

- Diesel Fuel Consumption for Backup Generator (Scope 1):
  - Diesel fuel consumption data for the on-site power generator was collected from fuel consumption records.
- Institution-Owned Vehicles (Scope 1):
  - Fuel consumption data for college-owned vehicles was collected, focusing on gasoline usage and operational activity, by calculating the total distance traveled.
- Electricity Consumption (Scope 2):
  - Monthly electricity consumption data for all college buildings were obtained from official electricity meters and utility records.
- Refrigerant Fugitive Emissions (Scope 1):
  - Refrigerant-related fugitive emissions from air-conditioning systems and refrigerators were included as an additional Scope 1 emission source. Due to the absence of complete maintenance and recharge records for 2025, refrigerant emissions were estimated using an engineering-based approach based on the actual equipment count, assumed refrigerant type, average refrigerant charge, and annual leakage/recharge rate.

By establishing clear system boundaries and focusing on verifiable data sources, this study ensures a reliable and transparent carbon footprint assessment of the Industrial Technical College.

In addition to the primary emission sources examined in this study, a review of other potential Scope 1 emission sources was conducted. The assessment confirmed that all laboratory, workshop, and support equipment within the Industrial Technical College operates exclusively on electricity. No gaseous fuels are used for boilers, heaters, or laboratory processes, and no combustion-based equipment is present within the campus facilities.

Consequently, all energy-related emissions associated with laboratory and technical activities are fully captured under purchased electricity consumption (Scope 2). Direct emissions under Scope 1 are therefore associated with diesel consumption for backup generators, gasoline use by college-owned vehicles, and estimated fugitive refrigerant emissions from air-conditioning and refrigeration equipment. Similarly, Scope 2 emissions were confined to purchased electricity consumed within the academic and administrative buildings of the Industrial Technical College. Electricity consumption associated with staff accommodation, hotel facilities, or other independently managed entities was excluded to maintain clearly defined organizational and operational boundaries.

This approach ensures complete coverage of relevant emission sources within the defined scopes, while maintaining transparency and consistency with internationally recognized carbon accounting frameworks.

C. Emission Calculation Methods

The carbon footprint of the Industrial Technical College was quantified using internationally recognized carbon accounting frameworks to ensure methodological robustness, transparency, and reproducibility. The assessment primarily follows the GHG Protocol Corporate Accounting and Reporting Standard, which provides a comprehensive and widely adopted framework for organizational-level greenhouse gas accounting, boundary definition, and emission categorization [15]. This framework has been extensively applied in carbon footprint assessments of higher education institutions and public-sector organizations.

Activity-based data collected from institutional records were systematically converted into greenhouse gas emissions and expressed in carbon dioxide equivalent (CO_2e), allowing emissions from different sources to be aggregated and compared on a consistent basis. This methodological approach is consistent with best practices reported in recent carbon footprint studies conducted within academic institutions and complex organizational settings [3,6].

By adopting these internationally validated frameworks and guidelines, the study ensures that the calculated emissions accurately represent the operational activities of the institution and allow meaningful comparison with similar assessments reported in the scientific literature.

1) General calculation approach

Greenhouse gas emissions were calculated using the standard emission factor–based approach, expressed as:

$$\sum CO_{2_e}\ Emmisions = (Activity\ Data\ X\ Emission\ Factor)$$

Where:

- Activity data represents measured consumption (e.g., liters of fuel, kilowatt-hours of electricity).
- The emission factor represents the amount of CO2 equivalent emitted per unit of activity, derived from internationally recognized sources and published papers.

Emissions were reported as carbon dioxide equivalent (CO_2e). Emission factors already expressed in CO_2e were applied directly. For non-CO_2 greenhouse gases, including refrigerants, CO_2e conversion was based on the 100-year Global Warming Potential (GWP_{100}) values from the IPCC Sixth Assessment Report (AR6) to ensure consistency and comparability with international GHG accounting practices.

All emission results are expressed in kilograms of CO2 equivalent and were aggregated to determine the total emissions for Scope 1 and Scope 2.

Refrigerant fugitive emissions were calculated using the following approach:

$$E_{ref} = \sum(m_i * GWP_{100,i})$$

where m_i is the estimated annual leaked or recharged mass of refrigerant i in kilograms, and $GWP_{100,i}$ is the 100-year Global Warming Potential of the corresponding refrigerant. For this study, GWP values were based on IPCC AR6. R-410A was treated as a 50/50 mass blend of HFC-32 and HFC-125, consistent with ASHRAE refrigerant designation data.

Based on the actual equipment count within the college, the inventory included 50 split air-conditioning units using R-410A and 4 refrigerators using R-134a. Due to the absence of complete refrigerant maintenance and recharge records for 2025, the refrigerant charge and annual leakage/recharge rates were estimated using an engineering-based approach. For split air-conditioning units, an average refrigerant charge of 1.2 kg per unit and an annual leakage/recharge rate of 10% were assumed. For refrigerators, an average refrigerant charge of 0.15 kg per unit and an annual leakage rate of 5% were assumed. Accordingly, the estimated annual refrigerant quantities were 6.00 kg of R-410A and 0.03 kg of R-134a.

2) Emission factors and activity data (Scope 1 & Scope 2)

The CO_2 emission factor for electricity generation in Libya was obtained from a locally published study analyzing actual power plant performance and national grid composition. In that study, the emission factor was estimated at 0.857 kg CO_2 per kWh, reflecting the fossil-fuel-dominant generation mix in Libya's electricity sector (Nassar et al., 2025) .[16]

Scope 2 emissions from purchased electricity were calculated using the location-based method. This method applies the average emission factor of the electricity grid from which the institution consumes electricity [17]. In the present study, the Libyan grid emission factor was used because the college purchases electricity from the national electricity grid and no market-based instruments, such as renewable energy certificates, green electricity contracts, or supplier-specific low-carbon electricity claims, were available or applied during the 2025 reporting year. Therefore, the Scope 2 results reported in this study represent location-based emissions associated with electricity consumption from the Libyan national grid.

To improve transparency and reproducibility, the emission factors used in this study are summarized in Table (1).

The table reports the emission factor value, unit, reference source, reference year, factor type, and justification for selection. Local emission factors were used where available, while internationally recognized default factors were adopted when Libya-specific factors were unavailable.

Due to the lack of peer-reviewed Libyan studies providing emission factors for diesel fuel and gasoline combustion, this study adopted internationally recognized values to ensure methodological consistency and comparability.

As shown in Table 1, the diesel emission factor was adopted as 2.68 kg CO_2e/L, while vehicle emissions were estimated using a distance-based factor of 0.1636 kg CO_2e/km. These internationally recognized default factors were used because verified Libya-specific emission factors for diesel combustion and vehicle travel were not available for the reporting year. [18],[19]. These factors are widely applied in carbon footprint assessments and align with established guidelines, such as the IPCC Guidelines for National Greenhouse Gas Inventories, providing a reliable basis for quantifying Scope 1 emissions associated with institutional energy use and transport activities.

By relying on these standardized emission factors, the study ensures that the calculated carbon footprint accurately reflects the operational activities of the Industrial Technical College for the year 2025, while transparently acknowledging the absence of locally derived emission factors for Libyan fuels.

The carbon footprint assessment was conducted for the calendar year 2025, with all activity data—including electricity consumption, diesel fuel usage for backup generators, and gasoline consumption for college-owned vehicles—collected exclusively for this year from official electricity bills, fuel purchase invoices, and transport logs. All emissions were converted to carbon dioxide equivalent (CO_2e) to enable aggregation of Scope 1 and Scope 2 emissions.

In addition, the college operates two backup generators with rated capacities of 500 kVA and 60 kVA, which are used to supply electricity during grid power outages. Electricity consumption for all academic and administrative buildings is monitored through two official electricity meters, with monthly readings systematically recorded. For the purpose of this study, aggregated annual electricity consumption data for the year 2025 were used in the carbon footprint calculations.

These operational characteristics establish a transparent basis for quantifying Scope 1 emissions associated with on-site fuel combustion and Scope 2 emissions arising from purchased electricity consumption.

Table (2) summarizes the activity data collected for 2025, including electricity consumption, transportation activity, and diesel fuel use, which serve as the basis for the carbon footprint calculations.

Table 1. Emission factors used for the carbon footprint inventory.

Emission source	Scope	Emission factor	Unit	Source / Reference year	Factor type	Justification for selection
Purchased electricity	2	0.857	kg CO_2/kWh	Nassar et al., 2025	Local / location-based	Represents the Libyan national electricity grid emission factor and reflects the fossil-fuel-dominant grid mix.
Diesel fuel for backup generators	1	2.68	kg CO_2e/L	IPCC / international default factor	Default / international	Used due to the absence of verified Libya-specific diesel combustion emission factors.
Gasoline use by college-owned vehicles	1	0.1636	kg CO_2e/km	Climatiq / international distance-based factor	Default / international	Used because detailed fuel consumption records were unavailable; vehicle emissions were estimated using a distance-based approach.
R-410A refrigerant	1	2.256	kg CO_2e/kg	IPCC AR6 + ASHRAE composition	Estimated / GWP-based	Used for estimated fugitive emissions from split AC systems.
R-134a refrigerant	1	1.530	kg CO_2e/kg	IPCC AR6	Estimated / GWP-based	Used for estimated fugitive emissions from refrigerators.

The emission factors described above were subsequently applied to calculate the carbon dioxide equivalent (CO_2e) emissions for each source. A summary of the activity data, corresponding emission factors, and resulting emissions for the year 2025 is presented in Table 3, which provides a consolidated overview of Scope 1 and Scope 2 emissions for the Industrial Technical College. This table serves as the basis for the analysis and

Table 2. Summary of Collected Activity Data .

		Rated Capacity (kVA)	Diesel Consumption(Liters/year)
Generator	Generator 1	500 kVA	1950 L
	Generator 2	60 kVA	230 L
	Total Diesel Consumption		**2180 L**
Vehicle Type		**Number of Vehicles**	**Annual Distance Traveled (km)**
	Staff Bus	1	15600 km
	College Cars (Travel Use)	6	46800 km
	Total Distance Traveled		**62400 km**
Electricity Consumption		**Quarterly**	**Electricity Consumption (kWh)**
	Electricity Meter No. 1	Q1	77490 kWh
		Q2	78350 kWh
		Q3	83520 kWh
		Q4	79215 kWh
	Total consumption		**318575 kWh**
	Electricity Meter No. 2	Q1	17220 kWh
		Q2	17410 kWh
		Q3	18560 kWh
		Q4	17600 kWh
	Total consumption		**70790 kWh**
	Total Electricity Consumption		**389365 kWh**
Refrigerant source		**Number of**	**Estimated annual refrigerant quantity**
	Split air-conditioning units	50	6 kg
	Refrigerators	4	0.03 kg
	Total refrigerant quantity		**6.03 kg**

discussion of the institutional carbon footprint presented in the following section.

It should be noted that the above studies generally assessed larger university campuses or multi-faculty institutions, often including several colleges and a broader range of academic and service buildings. In contrast, the present study focuses on a single technical college with a smaller operational scale and defined organizational boundaries. Therefore, while absolute emission totals differ, the pattern of emission contributions remains consistent: purchased electricity is the primary driver of Scope 1 and Scope 2 emissions when Scope 3 categories are excluded. This benchmarking supports the robustness and plausibility of the results obtained in the present study.

Table 3. Carbon Footprint Calculation Summary of the Industrial Technical College for 2025 (Scope 1 and Scope 2 Emissions)

Emission Source	**Scope**	**Activity Data**	**Unit**	**Emission Factor**	**Unit**	**CO_2e Emissions**
Diesel for backup generator.	Scope 1	2180	Liter	2.68	kg CO_2e/L	5842.4 kg CO_2e
Gasoline for college-owned vehicles	Scope 1	62400	km	0.1636	kg CO_2e/km	10208.64 kg CO_2e
Purchased electricity	Scope 2	389365	kWh	0.857	kg CO_2e/kWh	333685.8 kg CO_2e
Refrigerant fugitive emissions	Scope 1	6.00 kg R-410A + 0.03 kg R-134a	kg	2,256 and 1,530	kg CO_2e/kg	13,578.90 kg CO_2e
Total	—	—	—	—	—	363315.74 kg CO_2e

D. Data Analysis

The calculated greenhouse gas emissions were analyzed by disaggregating total CO_2e into major activity sectors aligned with the defined Scope 1 and Scope 2 system boundaries. Specifically, total emissions were classified into:

i. purchased electricity consumption (Scope 2).

ii. diesel combustion for backup generators (Scope 1).

iii. gasoline consumption associated with institution-owned vehicles (Scope 1).

iv. estimated refrigerant fugitive emissions from air-conditioning and refrigeration equipment (Scope 1)

Due to the unavailability of detailed fuel consumption records, vehicle emissions were estimated using a distance-based emission factor.

This sector-based breakdown enables identification of emission hotspots and supports targeted mitigation planning, consistent with standard institutional carbon accounting practices [17,20].

To contextualize the carbon footprint results of the Industrial Technical College, the obtained annual emissions were benchmarked against published carbon footprint inventories of comparable higher education institutions worldwide. In this study, the total annual emissions were estimated at 363.32 tCO_2e for Scope 1 and Scope 2 combined, with electricity consumption contributing approximately 91.8% of the total.

For comparison, several peer-reviewed studies reported the following annual carbon footprint values for higher education institutions under similar reporting boundaries (Scope 1 and Scope 2):

i. Giubarbi & Güvenç (2022) reported a total of approximately 4,200 tCO_2e/year for a technical university campus in Europe where laboratory and equipment electricity loads were significant sources of emissions.

ii. Jesuniño Aquino et al. (2024) found total annual emissions in the range of 3,500–7,800 tCO_2e/year for a higher education institution in Latin America, with electricity consumption again dominating the footprint.

iii. Rahman et al. (2025) determined about 9,000 tCO_2e/year at an Asian technical campus prior to mitigation measures, where purchased electricity was the highest contributor.

Furthermore, the analysis focused on identifying the most influential emission sources within the college. Emission contribution percentages were computed for each sector, allowing prioritization of mitigation strategies.

Such prioritization approaches are widely recommended in campus sustainability research, where reduction strategies are guided by the
relative weight of emission sources
(e.g., energy demand reduction, renewable energy integration, and operational efficiency improvements) [23,1].

Based on this analysis, the study proposes emission reduction opportunities targeting the highest-impact sectors to support the college's sustainability planning and carbon management initiatives.

E. Data Quality and Uncertainty Assessment

The reliability of the carbon footprint inventory depends on the quality of activity data and the emission factors used in the calculations. In this study, data quality and uncertainty were assessed using a qualitative screening approach based on data source, completeness, traceability, and consistency with the defined reporting boundary. In addition, indicative uncertainty ranges were assigned to the main activity data and emission factors to support interpretation of the results. These values are intended for uncertainty screening and methodological transparency, rather than as statistically derived confidence intervals.

Electricity consumption data were considered to have relatively high reliability because they were obtained from official electricity meters and utility records. An indicative uncertainty of ±2% was assigned to electricity activity data to account for possible meter reading, recording, and aggregation errors. Diesel consumption data were considered moderately reliable because they were based on institutional fuel consumption records for backup generators, and an indicative uncertainty of ±5% was assigned. Vehicle-related emissions were associated with higher uncertainty because they were estimated using total annual distance travelled and a distance-based emission factor rather than direct gasoline consumption records; therefore, an indicative uncertainty range of ±15–20% was assigned.

Refrigerant fugitive emissions were assigned the highest uncertainty among the quantified sources. Although the number of cooling devices was based on the actual equipment count within the college, the refrigerant charge and annual leakage/recharge rates were estimated using an engineering-based approach due to the absence of complete refrigerant maintenance and recharge records for 2025. Accordingly, an indicative uncertainty of ±35% was assigned to refrigerant-related emissions.

Additional uncertainty arises from the emission factors applied. The Libyan grid emission factor provides a location-specific estimate for Scope 2 emissions; however, it may vary with changes in the national electricity generation mix, power plant efficiency, fuel quality, and operating conditions. Therefore, an indicative uncertainty of ±5% was assigned to the grid emission factor. For diesel fuel, vehicle emissions, and refrigerant-related emissions, internationally recognized default emission factors and GWP values were used due to the absence of verified Libya-specific factors.

Overall, the uncertainty of the inventory is mainly influenced by the Libyan grid emission factor, vehicle activity estimation, and refrigerant leakage assumptions. Because purchased electricity remains the dominant emission source, uncertainty in the grid emission factor has the largest influence on the total carbon footprint. The main sources of uncertainty and proposed improvement actions are summarized in Table 4.

The uncertainty ranges presented in Table 4 were used to support qualitative interpretation of data reliability and to identify the most uncertain emission sources. They were not applied as correction factors and therefore do not modify the reported point estimates of emissions. Accordingly, the total carbon footprint remains reported as 363.32 tCO_2e/year, while the uncertainty assessment highlights that the main sources requiring improved future data collection are vehicle fuel use and refrigerant maintenance records.

III. Results

This section presents the calculated carbon footprint results of the Industrial Technical College for the year 2025, based on the defined Scope 1 and Scope 2 system boundaries. The results are reported as total annual CO_2e emissions and further disaggregated by emission source to highlight the main contributing sectors and support benchmarking with similar higher education institutions.

A. Sector-wise Carbon Emission Distribution

The total annual carbon footprint of the Industrial Technical College for 2025 amounted to approximately 363.32 tCO_2e for Scope 1 and Scope 2 emissions. Sectoral emissions are detailed as shown in Figure 1.

Figure 1 illustrates the relative contribution of each emission source to the total carbon footprint. Purchased electricity remained the dominant contributor, accounting for approximately 91.8% of total emissions. Refrigerant fugitive emissions represented about 3.7%, while college-owned vehicles and diesel generators contributed approximately 2.8% and 1.6%, respectively.

B. Annual Summary of Emissions

The total annual emissions, presented in Table 5, summarize the contributions of each sector and provide a baseline for comparison with other higher education institutions. This baseline forms the foundation for the development of mitigation strategies.

- Electricity consumption: 333.7 tCO_2e (~91.8% of total).
- Refrigerant fugitive emissions:13.6 tCO_2e (~3.7% of total).
- College-owned vehicles: 10.2 tCO_2e (~2.8% of total).
- Diesel generators: 5.8 tCO_2e (~1.6% of total).

Table 4. Data quality and uncertainty assessment.

Emission source / data item	Data source / basis	Data quality	Indicative uncertainty	Main uncertainty source	Improvement action
Purchased electricity activity data	Official electricity meters and utility records	High	±2%	Meter reading, recording, and annual aggregation errors	Monthly verification and digital archiving of meter readings
Libyan grid emission factor	Published Libya-specific grid emission factor	Moderate	±5%	Changes in generation mix, plant efficiency, fuel quality, and operating conditions	Periodically update the grid emission factor using recent national data
Diesel generators	Institutional fuel consumption records	Moderate	±5%	Fuel record completeness and lack of detailed generator operating logs	Link fuel records with generator operating hours and maintenance logs
College-owned vehicles	Annual distance travelled and distance-based emission factor	Moderate to low	±15–20%	Use of distance-based factor instead of actual gasoline consumption	Record actual fuel consumption by vehicle and trip purpose
Refrigerant fugitive emissions	Actual equipment count and engineering-based estimate	Moderate to low	±35%	Estimated refrigerant charge and leakage/recharge rates	Establish refrigerant maintenance, recharge, and leakage records
Default fuel and vehicle emission factors	International default factors	Moderate	±10–20%	Differences from local fuel quality, vehicle type, and operating conditions	Adopt Libya-specific factors when available
Scope 3 categories	Not quantified in this inventory	Unavailable	Not quantified	Lack of verified data for commuting, waste, paper, water, and travel	Develop a structured Scope 3 data collection system

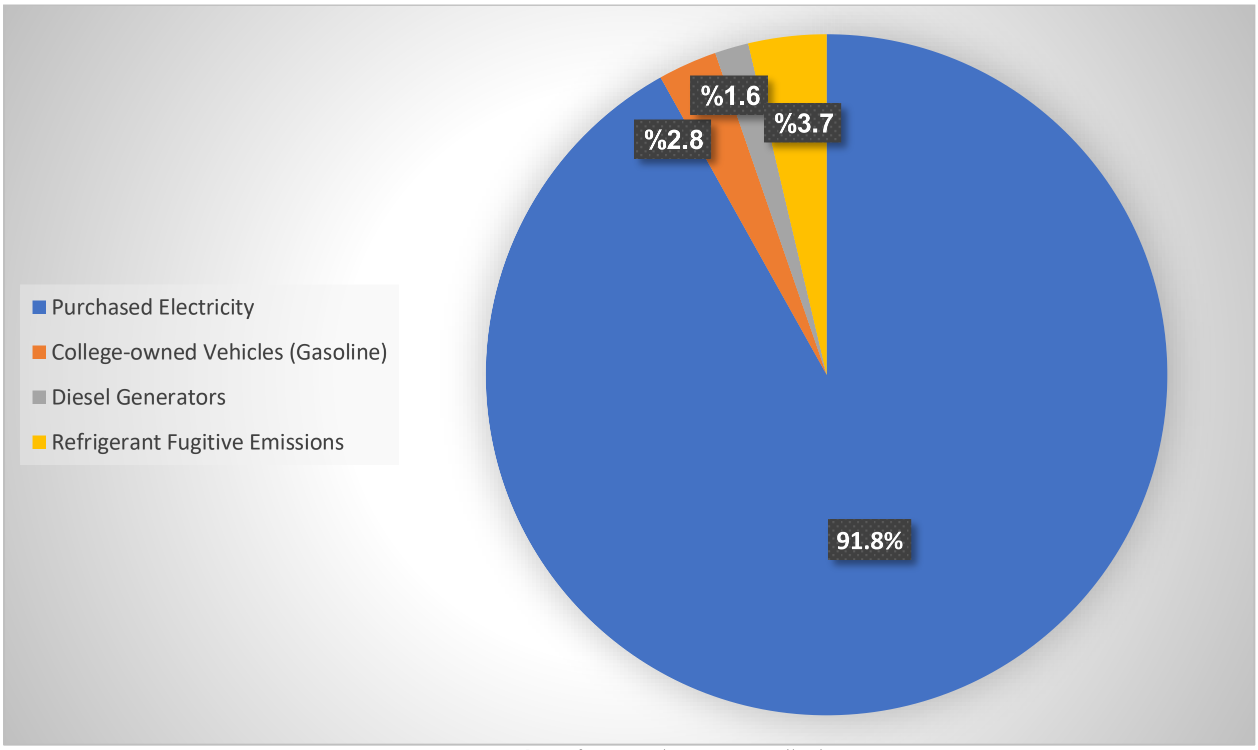

Figure 1: Pie chart of sector-wise CO_2e contributions.

Table 5. Carbon Footprint Calculation Summary of the Industrial Technical College for 2025 (Scope 1 and Scope 2 Emissions)

Emission Source	**Scope**	**Activity Data**	**Unit**	**Emission Factor**	**Unit**	**CO_2e Emissions**
Diesel for backup generator.	Scope 1	2180	Liter	2.68	kg CO_2e/L	5842.4 kg CO_2e
Refrigerant fugitive	Scope 1	6.03	kg	2,256 and 1,530	kg CO_2e/kg	13,578.90 kg CO_2e
Gasoline for college-owned vehicles	Scope 1	62400	km	0.1636	kg CO_2e/km	10208.64 kg CO_2e
Purchased electricity	Scope 2	389365	kWh	0.857	kg CO_2e/kWh	333685.8 kg CO_2e
Total	—	—	—	—	—	363315.74 kg CO_2e

Table 6. Carbon intensity indicators for the Industrial Technical College

Indicator		**Basis**	**Value**
Area-based intensity		15,914 m^2	22.8 kg CO_2e/m^2·year
Student-based intensity		400 students	908.3 kg CO_2e/student·year
Employee-based intensity		55 faculty + 35 staff = 90 employees	4,036.8 kg CO_2e/employee·year
Per-capita intensity		400 students + 90 employees = 490 persons	741.5 kg CO_2e/capita·year

Table 7. Benchmark comparison of Scope 1 and Scope 2 carbon footprint results for the Industrial Technical College and similar higher education institutions worldwide.

Reference	**Institution Type**	**Scope 1+2 (tCO_2e/year)**	**Notes**
Giubarbi & Güvenç (2024)	Technical University	~4,200	Lab-intensive campus in Europe
Jesuiño Aquino et al. (2024)	HE Institution	3,500–7,800	Latin America
Rahman et al. (2025)	Technical Campus	~9,000	Asia, pre-mitigation
This study	Industrial Technical College	~363	North of Africa

C. Carbon Intensity Indicators

To improve the comparability of the carbon footprint results, additional carbon intensity indicators were calculated based on building area and institutional population. The built-up area of the Industrial Technical College was estimated at 15,914 m^2 using Google Earth measurements. Based on the total annual emissions of 363.32 tCO_2e, the area-based carbon intensity was calculated at approximately 22.8 kg CO_2e/m^2·year. In addition, population-based indicators were estimated using available institutional data. The college has approximately 400 students, 55 faculty members, and 35 technical and administrative staff, giving a total institutional population of approximately 490 persons. Accordingly, the carbon intensity indicators were estimated at 908.3 kg CO_2e/student·year, 4,036.8 kg CO_2e/employee·year, and 741.5 kg CO_2e/capita·year. These carbon intensity indicators are summarized in Table 6.

D. Comparison with Global Benchmarks

To evaluate the environmental performance of the Industrial Technical College, the calculated emissions were compared with carbon footprints reported for selected higher education institutions worldwide, as summarized in Table 7 [10,7,8].

The comparison provides a general benchmark for interpreting the magnitude of the college's Scope 1 and Scope 2 emissions; however, direct comparison of absolute emissions should be interpreted with caution. Differences among institutions may arise from several factors, including campus size, number of students and employees, building functions, climate conditions, operational intensity, electricity consumption patterns, and the national grid emission factor used for Scope 2 calculations. In addition, institutional carbon footprint studies do not always apply identical inventory boundaries. Some studies report only Scope 1 and Scope 2 emissions, while others include selected Scope 3 categories such as commuting, waste, paper consumption, water use, procurement, and business travel [21–23]. These methodological differences can significantly affect the reported total emissions.

In this context, the relatively lower absolute emissions reported for the Industrial Technical College should not be interpreted solely as evidence of better environmental performance. Instead, the result mainly reflects the smaller institutional scale, the exclusion of Scope 3 emissions, and the defined operational boundary of the present study. Therefore, carbon intensity indicators, such as emissions per unit floor area, per student, per employee, and per

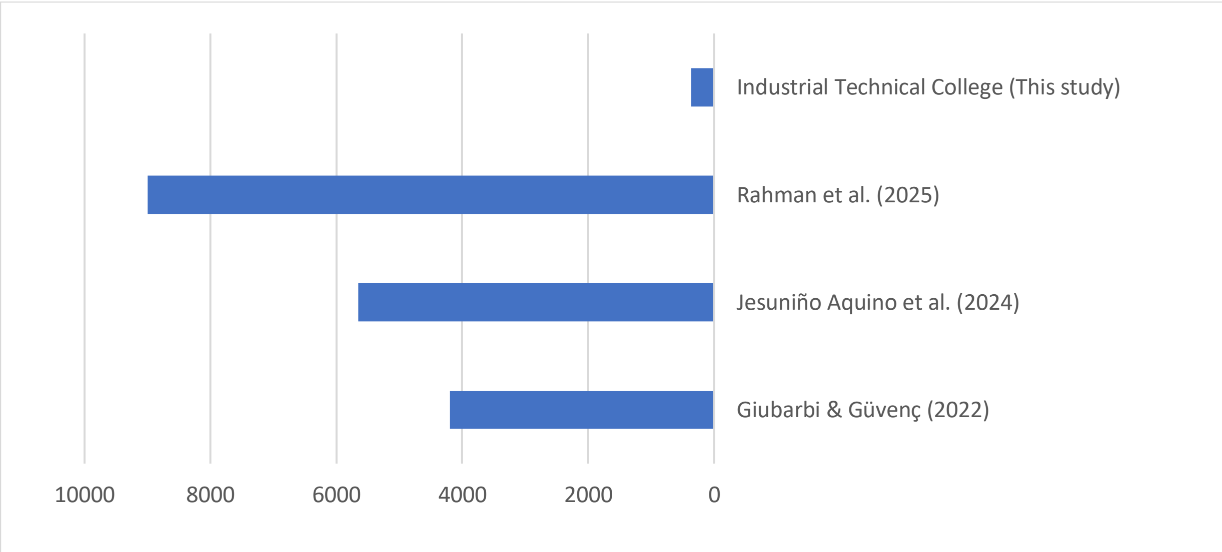

Figure 2: Benchmarking of Scope 1 and Scope 2 carbon footprint results against comparable higher education institutions.

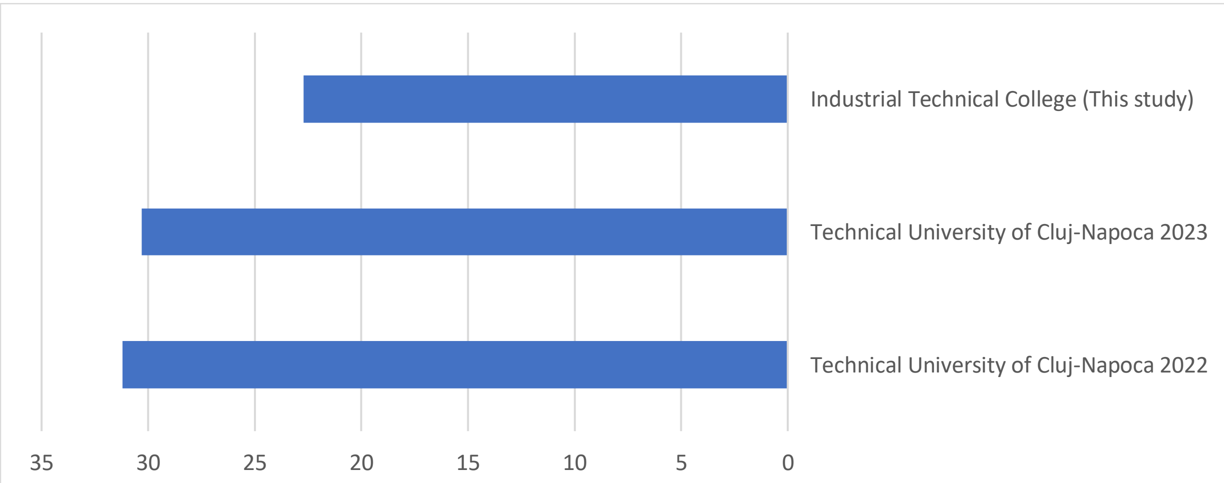

Figure 3: Benchmarking of Scope 1 and Scope 2 carbon footprint results against comparable higher education institutions.

capita, provide a more meaningful basis for benchmarking than total emissions alone.

For improved visual interpretation, the benchmark results presented in Table 7 are illustrated in Figure 2. In the case of studies reporting emission ranges, such as Aquino et al. [23], the midpoint value was used for visualization purposes. The figure is intended to provide a broad comparative context rather than a direct ranking of institutional performance.

For further benchmarking, the area-based carbon intensity of the Industrial Technical College was compared with similar higher education institutions reporting emissions normalized by campus area. After including estimated refrigerant fugitive emissions, the college recorded an area-based carbon intensity of approximately 22.8 kg $CO_2e/m^2\cdot$year. This value is lower than the values reported for the Technical University of Cluj-Napoca, namely 31.2 kg $CO_2e/m^2\cdot$year in 2022 and 30.3 kg $CO_2e/m^2\cdot$year in 2023 [27]. This comparison is illustrated in Figure 3.

Overall, the benchmark comparison suggests that the Industrial Technical College has relatively low Scope Overall, the benchmark comparison suggests that the Industrial Technical College has relatively low Scope 1 and Scope 2 emissions compared with larger institutions. However, the comparison also confirms the importance of improving data coverage, especially for Scope 3 categories, and using normalized carbon intensity indicators to support more reliable institutional benchmarking in future assessments.

IV. DISCUSSION

The results of the carbon footprint assessment indicate that purchased electricity remains the dominant contributor to the Industrial Technical College's emissions after including estimated refrigerant fugitive emissions. The total annual carbon footprint increased from 349.74 tCO_2e to approximately 363.32 tCO_2e. Purchased electricity accounted for approximately 91.8% of total Scope 1 and Scope 2 emissions, while estimated refrigerant fugitive emissions represented about 3.7%. College-owned vehicles and diesel generators contributed approximately 2.8% and 1.6%, respectively.

This pattern is consistent with previous studies, where electricity typically represents the largest emission source in higher education institutions, especially when Scope 3 emissions are excluded [21].

The inclusion of refrigerant fugitive emissions provides a more complete representation of Scope 1 emissions. Although the estimated refrigerant mass is relatively small, its contribution is notable due to the high global warming potential of refrigerants such as R-410A and R-134a. Refrigerant emissions became the second-largest emission source after purchased electricity, exceeding the individual contributions of diesel generators and college-owned vehicles. However, this category is associated with higher uncertainty because refrigerant charge and leakage/recharge rates were estimated using an engineering-based approach in the absence of complete maintenance and recharge records.

The high contribution of electricity is primarily due to the reliance on grid power for academic and administrative buildings, whereas the limited operational hours of diesel generators and low mileage of college vehicles reduce their relative impact. This highlights the importance of focusing mitigation strategies on energy efficiency and renewable energy integration.

In terms of mitigation, the proposed interventions—including the deployment of photovoltaic systems, optimization of building energy use, and efficient scheduling of equipment and HVAC systems—are expected to significantly reduce Scope 2 emissions. In addition, refrigerant-related emissions can be reduced through systematic maintenance of air-conditioning systems, regular leak detection, proper refrigerant handling, and gradual replacement of old cooling equipment with lower-GWP alternatives. Transport-related emissions, while currently minor, could be further minimized by promoting efficient vehicle use and considering electrification or alternative transport strategies.

Future scenarios could also include expansion of renewable energy capacity, improvement of internal mobility and transport systems, and implementation of recycling and waste reduction measures. These actions not only lower carbon emissions but also enhance the overall sustainability profile of the college.

The exclusion of Scope 3 emissions limits the comprehensiveness of the inventory, particularly because higher education institutions may have relevant indirect emissions from commuting, academic travel, waste, paper consumption, water use, and purchased goods. Accordingly, the results should be interpreted as an operational Scope 1 and Scope 2 baseline rather than a full institutional carbon footprint. Establishing structured data collection systems for Scope 3 categories is recommended for future assessments.

V. RECOMMENDATIONS

Based on the findings and discussion, the following recommendations are proposed for practical implementation:

- Short-term (1–2 years):
  - Monitor and optimize electricity use in classrooms, offices, and laboratories.
  - Educate students and staff on energy-saving practices, including turning off unused equipment.
- Medium-term (3–5 years):
  - Implement photovoltaic systems on campus, prioritizing high-consumption areas such as parking areas and rooftops.
  - Upgrade lighting and HVAC systems to energy-efficient alternatives.
  - Introduce incentives for staff and students to use sustainable transportation options.
- Long-term (>5 years):
  - Integrate carbon management practices into campus planning and decision-making.

- Expand renewable energy coverage to reduce dependency on grid electricity.
- Link carbon footprint findings to applied research projects, fostering innovative sustainability solutions within the college.

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