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Assessment of the carbon footprint of an Italian football team during a sport year

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ABSTRACT

This study calculates the corporate carbon footprint (CCF) of the main Italian football club, A.S. Roma, for the entire season 2023/2024, providing a comprehensive analysis of its greenhouse gas (GHG) emissions across its areas of activity. The methodology follows the GHG Protocol, breaking down the emissions into Scope 1, Scope 2, and Scope 3. Results show that the total CCF for the 2023/24 season is 6857 tCO_2e, including direct emissions from fuels, refrigerants, and corporate vehicles (Scope 1), indirect emissions from purchased energy (Scope 2), and indirect emissions from purchased goods and services, energy-related activities, logistics, waste management, business travel and accommodation, and employee commuting (Scope 3). Scope 3 emissions dominate with 82.8% of the total. The key drivers are the team's travel and accommodation, goods and services, and staff commuting. As for the area of operations, stadium operations account for 59.8% of emissions, training facilities 23.6%, and internal organization 16.6%. A home game emits 46 tCO_2e, with food and beverage accounting for 78% of event-related emissions. Overall, the study provides a structured and replicable methodological framework for carbon footprint accounting in professional sport organizations, supporting year-to-year comparability and the identification of priority levers for targeted decarbonization.

1. Introduction

The scientific community agreed on the accelerated pace and complexity of climate change in the early 2000s (IPCC et al., 2018). Since the first industrial revolution, the planet's median temperature has increased by over 1.1 °C, with global warming currently growing per decade due to past and ongoing emissions (Ripple et al., 2020). The drastic climate change caused by human activities is a growing concern that could lead to severe disruption of social, ecological, and economic systems for future generations (Ritchie et al; Ross and Leopkey, 2017). Achieving a climate-neutral world by 2050 will require significant transformation across all economic value chains (United Nations, 2015; Tziralis et al., 2008). In this context, it is important to recognize the roles of various actors in this transformation. All actors have a key role to play in the transition to climate neutrality. Within this transition, sustainability has become a central organizing concept for policy, research, and corporate strategy.

The concept of sustainability is gaining increasing relevance within the scientific literature (Wackernagel, 1996; Ahmed et al., 2020; Mallen et al., 2010; Asdrubali et al., 2024; Ulloa-Hernández et al., 2023; Gollagher and Fastenrath, 2023). It is crucial to highlight how this concept is now also widely integrated into the business sector. As articulated in the ESG (Environmental, Social, and Governance) parameters, sustainability has become a crucial strategy for companies (Danish et al., 2020; McCullough and Cunningham, 2010). This strategy allows companies to stabilise and increase their market share and demonstrates their attention to the community's future goals. Companies that adopt sustainable practices show a concrete commitment to improve environmental, social and governance conditions, thus contributing to sustainable and responsible progress (UNFCCC The Paris Agreement, 2015; Hautbois and Desbordes, 2023).

The predominant narrative for achieving this change is to modify the behavior of individuals (Ross and Leopkey, 2017; Hoekstra and Wiedmann, 2014; Collins et al., 2009). This is defined as behavior that consciously seeks to minimize the negative impact of one's actions on the natural and built world. Sport is a highly relevant forum for examining the continued validity of individual behavioral interventions, as it reaches large populations and offers a highly visible stage for promoting messages that seek to influence environmental behavior (McCullough et al., 2020a, 2020b; Daddi et al., 2022).

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Sports events can have a high environmental impact (Wicker and Thormann, 2024; Grofelnik et al., 2023, 2024; Wicker, 2019), for example due to supporters' travel activities to attend the events (Loewen and Wicker, 2021; Ballarano et al., 2022; Cheng et al., 2025; Cooper and McCullough, 2021) and waste connected to spectators and daily maintenance (Collins et al., 2009; Heck, 2019; Bianchini and Rossi, 2021). Therefore, sports organizations must understand the impacts of the changing climate and how to reduce them in the future (United Nations Framework Convention on Climate Change, 2020; Jones, 2008; Gholami et al., 2016). For this reason, the United Nations (UN) has included sport in its global climate action framework, aiming for carbon neutrality in sport by 2050 (Gollagher and Fastenrath, 2023). International cooperation is required to reduce GHG emissions and contribute to the global issue of climate change.

Some sports organizations have started taking the initiative by implementing environmental programs to mitigate environmental impacts, especially those involved with big leagues and events. For example, the Germany 2006 FIFA World Cup aimed to promote energy consumption from renewables and enhance transport mobility programs' effectiveness (McCullough et al., 2020a; Tóffano Pereira et al., 2020; Herold et al., 2024). The National Football League's (NFL) 2008 initiatives included urban tree planting, increasing renewable energy sources, and recycling waste (Perkumienė et al., 2023; Crockett, 1994). The 2020 Tokyo Olympics aimed for carbon neutrality by building eco-friendly stadiums and transport facilities running on renewable energy sources. Toyota, one of the Olympic partners, pledged to supply zero-emission vehicles, including hydrogen cars, to the 2020 Tokyo Olympics (Ross, 2005). All the venues for the 2022 Beijing Olympics are operated by renewable energy. FIFA targeted to achieve carbon neutrality by the 2022 World Cup in Qatar planning measures such as energy-efficient infrastructure, environmental resource management, and carbon offsetting programmes to compensate residual emissions (Lein, 2016). Taking all the existing knowledge together, the literature provides some useful but piecemeal information on a given source of emissions or a given set of operational conditions in professional sports. Such a situation highlights the need for an organization-level carbon footprint analysis.

If sports organizations worldwide want to contribute to climate change mitigation, they must first acknowledge their contribution to climate change and reduce their carbon footprint. They need to know how much GHG emissions they produce, in the different sectors, and how much they can reduce. Available assessments in the sport context have primarily focused on specific components such as travel demand, waste management, and the carbon footprints of large events (Müller and Gaffney, 2018). For example, in the study provided by (Tóffano Pereira et al., 2019), the carbon footprint of the English Premier League clubs' travel habits was assessed, finding that 61% of the carbon impact is accounted for by transportation. Another study evaluated the 2018–2019 season's carbon footprint of soccer fans traveling to Bundesliga games in Germany. The results showed a Bundesliga fan's average annual carbon footprint was 311.1 kg of CO_2e emissions, with 70% of those emissions coming from personal transportation. For the whole Bundesliga season, the combined carbon footprint of all supporters was 369,765 tons CO_2e (Loewen and Wicker, 2021).

Several organizations have tried to measure and monitor proximity through metrics and sustainability indicators, in the perspective of Sustainable Development, considering it as "progress that meets the needs of the present without compromising the ability of future generations to satisfy their own needs", as defined in the Brundtland Report (United Nations Report of the, 1987). The sports industry, in particular professional sports organizations, has an enormous capacity to influence consumer behavior (Horne, 2007). Various stakeholders make up the "modus vivendi" of these organizations (e.g., members, employees, sponsors). Economic, social, and environmental sustainability is becoming a dominant theme in society, and the visibility of sports allows reaching an audience of millions of people from all social classes (Kucukvar et al., 2021).

At the level of sports organizations, sustainability appears as a strategy that aims to improve economic and social objectives (Rozhdestvenskaya et al., 2021). The implementation of sustainability initiatives not only boosts the experience lived by the fans but also fosters a closer relationship with the community. Sport can be seen as an instrument that generates dynamics that integrate wills, enhance changes, and create significant impacts on the cultural, social, and environmental systems (Smulders, 2012). In this way, sport, represented by the respective organizations and companies, public or private, can be considered an important agent in terms of sustainability, acting accordingly to the principles inherent to the concept, and promoting a set of initiatives in this area, including health and well-being.

One way that sports organizations have sought to differentiate themselves and create stronger bonds with their current and prospective customers (i.e., fans) is through corporate social responsibility (CSR) initiatives (The Sport Journal Premier League). The focus on sustainability in sport has grown substantially over the past two decades among practitioners and academics. Sports organizations that have demonstrated their commitment to environmental sustainability efforts are now seeking ways to monetize their efforts by incorporating environmentally focused sponsorships.

Over the last few decades, organizations have gained better awareness of environmental sustainability-related issues. Companies have realized that sustainability constitutes a means of differentiation, which is crucial for increasing productivity and competitiveness (Tóffano Pereira et al., 2020). The adoption of proactive sustainability management has direct and positive repercussions on business competitiveness. The concept of the carbon footprint (CF), which measures CO_2e or other greenhouse gas emissions, is becoming increasingly widespread (Piccerillo et al., 2023). This indicator can be applied to companies and organizations, with the concept of corporate carbon footprint (CCF) being particularly attractive, especially considering the demands within the framework of the Kyoto Protocol (Perkumienė et al., 2023). Different approaches have been used to estimate CCF, but there is still no consensus regarding certain matters, such as the inclusion of CO_2e or other gas emissions, scope (whether to include only direct emissions or also indirect emissions), and methodology (classical life-cycle analysis, input-output techniques, etc.) (Gandola and Asdrubali, 2024; Wakernagel and Rees, 1997).

However, the uptake of these frameworks in sport, particularly in professional football, remains limited. Despite the growing focus on sustainability, there is still a relative lack of representation of environmental issues in sports literature, particularly in football (Selectra How Much Energy Does). In particular, comprehensive carbon footprint assessments at club level, covering all Greenhouse Gas Protocol (GHG Protocol) scopes and the full spectrum of operational activities, remain rarely reported for major professional football clubs. Existing contributions have often focused on specific components (e.g., travel demand or event-related impacts) rather than organization-wide accounting suitable for benchmarking and targeted decarbonization planning (Müller and Gaffney, 2018). The GHG Protocol was developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), which represents the internationally recognized standard for corporate greenhouse gas accounting. The framework defines clear system boundaries within which emissions are calculated, including temporal, organizational, and operational boundaries (Loewen and Wicker, 2021).

The FA in England, for instance, states that sustainability has been a key issue for them since 2007, and they employ a sustainability team. However, their focus is primarily on their direct impacts as an employer and venue manager, not on the wider impacts of the game.

The original contribution of this study is the assessment of the carbon footprint of a major Italian football club throughout the season, extending beyond matchday emissions to include the full set of operational activities under the GHG Protocol Scopes 1, 2, and 3. The work aims to analyze every single aspect of a club's day-to-day life in detail. It starts with sporting events, the clubs' core business, assessing the impact of athletes and fans traveling to the stadium and the associated consumption before, during, and after the event. The analysis covers the environmental impact of company resources and club-owned vehicles, and was also extended to include employees by evaluating the emissions associated with commuting between home and the workplace. Furthermore, the logistics related to the procurement of assets for retail operations is also assessed. A further distinguishing element that gives originality to this study is the application of the methodology to all team groups, including the main team, women's teams and youth teams. This ensures that the methodology is as thorough as possible.

The paper is structured as follows. Section 2 describes the problem and sets out the calculation approach for carbon footprint, defining the approach for its calculation. It defines the segmentation of the classification of the emissions into Scopes 1, 2, and 3 under the GHG Protocol, and discusses each of them in terms of data sources, calculation, and drivers. Subsequently, section 2 illustrates the case study, applying the approach on a top-flight football club competing in the Italian Football Federation (FIGC) and UEFA championships. It quantifies the 2023/2024 seasonal emissions of the club, splitting them into categories and identifying the significant sources of their environment-related impacts. In Section 2.2, data collection becomes the focus, defining the process of collecting data on sources of the emissions, data collection difficulties, and methods of achieving reliability. Section 2.3 defines the calculation of carbon footprint, with findings discussed in section 4.

Section 4 placed these findings in the context of established research and industry best practice and identifying key sustainability challenges and improvement opportunities. Finally, Section 5 present the conclusions, identifying the limitations of this research and future research directions.

This is an original, in-depth carbon footprint study of a football club that examines all of the areas of operation available in detail. It represents one of the most comprehensive assessments of the environmental footprint of a professional sports organization published to date, contributing a structured methodological reference for future studies and sustainability initiatives.

2. Materials and method

This study applies a Corporate Carbon Footprint assessment to a professional football club during a full sporting season. This study focuses exclusively on the quantification of greenhouse gas emissions expressed as carbon dioxide equivalents (CO_2e) and does not represent a full sustainability assessment, which would require the inclusion of additional environmental, social, and economic indicators. The following Fig. 1 outlines the CCF calculation methodology that is structured into several key phases.

First, it is necessary to analyze the assets and activities of the sports organization in order to define a comprehensive and unambiguous data collection strategy. Subsequently, the data collection processes are implemented across the different operational areas of the club, identifying any missing or unavailable information. These data gaps are then addressed through estimations, using analogies with similar case studies or plausible assumptions. Once the data have been gathered, the Carbon Footprint can be calculated using specific formulas, according to the GHG Protocol, based on emission factors corresponding to each reference activity. The results are also organized according to the structure of the Protocol, based on the degree of responsibility attributable to the organization. This framework distinguishes between direct and indirect emissions and, for the latter, provides a detailed classification according to the area from which they originate. In this study, the impact categories that encompass the main sources of greenhouse gas emissions during the sports seasons have been considered. Below is a brief description of the scopes and their respective categories.

- Scope 1 includes direct emissions resulting from activities under the control of the organization, such as the combustion of fossil fuels within club facilities (e.g., boilers, company vehicles, heating systems). This scope encompasses all sources directly managed by the organization, such as fuel use for heating and transportation. Scope 1 emissions are calculated using fuel consumption data, multiplied by an emission factor that reflects the environmental impact of each fuel type (e.g., diesel, petrol, or natural gas).
- Scope 2 refers to indirect emissions resulting from the purchase and use of energy, including electricity, steam, cooling, and heating acquired from third-party suppliers. Although these emissions are not generated directly by the club, they are a consequence of its activities—for instance, the energy used to power stadiums, gyms, offices, and other facilities. Scope 2 emissions can be estimated using regional emission factors or, alternatively, specific factors provided by energy suppliers, which indicate the amount of CO_2 equivalent generated per kilowatt-hour consumed.
- Scope 3 encompasses other indirect emissions, divided into the following categories: Category 1: includes water use, materials, merchandising, food, and beverages; Category 3: refers to energy-related activities from production to the point of consumption; Category 4: regards upstream transportation related to the delivery of goods and materials to the organization's facilities; Category 5: concerns waste management; Category 6: includes business travel and accommodation related to organizational activities; Category 7: covers employee commuting; Category 9: regards goods transportation sold by the company.

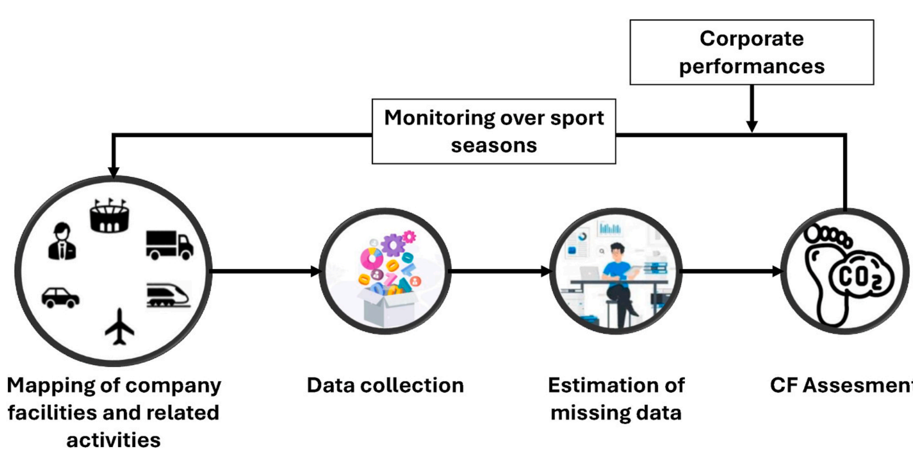

Fig. 1. Corporate carbon footprint calculation methodology.

- Scope 3 Other refers to emission sources that are relevant to the broader system but lie outside the defined operational boundary of the corporate carbon footprint. In this study, spectator mobility is reported under this category and presented separately from the main accounting results.

The environmental performance associated with both sporting and corporate results allows for the definition of standardized impact indicators (e.g., emissions per spectator or emissions per million euros of revenue), which enable continuous monitoring of environmental performance over time.

2.1. Case study description

The CCF calculation methodology was applied to a real case study for the 2023/2024 football season: A.S. Roma, one of the most important football clubs in Federazione Italiana Gioco Calcio (FIGC) and in The Union of European Football Associations (UEFA), which has more than 400 employees and more than 250,000,000 euros in revenues (A.S. Roma S.p.A, 2024). To support the management of a sports club's emissions and ensure both comparability between seasons and user involvement and empowerment, the CCF calculation is normalized on the main performance indicators of the sports context. CCF pertains to sports clubs that engage in several divisions. In contrast, it is only in the matches of the male first team that yield a considerable crowd. In particular, sixty matches encompassing friendlies, cup games, and league games together have attracted more than half a million spectators, as well as selling more than 800,000 tickets for home matches. As such, it was necessary that CCF normalization be designed for matches involving that particular team. Moreover, indicators encompassing club size include the number of employees and revenue figures. In addition, to raise awareness of the administration of CCF, home football matches attended by that team are considered. More specifically, several performance and emission monitoring indicators are proposed for the sports club. These include the total emissions produced by the club during the sporting season, emissions normalized by the number of matches played by the men's first team, emissions normalized by the total number of tickets sold for home matches over the season, emissions normalized by the number of employees working in sporting and administrative venues, and emissions normalized per unit of revenue equal to 100,000 euros. Normalization in this study refers to the process of calculating the Corporate Carbon Footprint based on certain operational and performance factors such as the number of matches played for the men's first team. This is done in a process that requires the total annual emissions to be measured in relation to the factor. Emissions are also reported according to the GHG Protocol classification into Scope 1, Scope 2, and Scope 3.

A.S. Roma operates on a structured sporting calendar between July 1 and June 30 that aligns with domestic and international football tournaments. This allows the club to synchronize financial planning, management of player contracts, sponsorship agreements, and operational logistics with the annual cycle of Serie A, Coppa Italia, Supercoppa Italiana, and UEFA tournaments. The sporting year is critical in generating revenues from broadcasting rights, matchday ticketing, and sponsorships, all of which are dependent on the performance of the club and supporters.

Team and employee structure at A.S. Roma is complex, with over 400 employees working on various aspects of the club's business. The men's first team competes in domestic and international competitions, averaging over 55 games per season, and the women's first team competes in Serie A Femminile, Coppa Italia Femminile, and UEFA Women's Champions League, playing around 40 games per annum. The club's youth sector is extensive, with teams in various age groups, including Primavera (Under-19), Under-18, Under-17, Under-16, Under-15, and Under-13, playing over 200 games per season. This structured youth development pipeline ensures a steady supply of talent while aligning with Roma's overall sporting objectives.

Organizing the logistics for over 300 matches per year involves a top-level operational system. Domestic travel for Serie A and Serie A Feminine matches typically involve high-speed trains and charter buses, while international fixtures require air travel, typically in the form of chartered flights for the men's first team. The typical away delegation for a first-team match involves 40–50 members, including players, coaching staff, and medical staff. Youth teams, although under the same pressures of travel, have a more budget-cutting modus operandi, generally with coach travel and shared rooms.

A.S. Roma's physical assets are integral to the business. The club's main training facility, Centro Sportivo Fulvio Bernardini, in Trigoria, accommodates 228 players, coaches, and support staff. The club also utilizes the Giulio Onesti Sports Center through a rental arrangement primarily for training of youth teams. Trigoria is fully owned, with control over energy management and facility enhancement, but rented facilities pose constraints on long-term sustainability endeavors. The Stadio Olimpico, the club's home stadium with a seating capacity of over 70,000, is the venue for all official games. Roma does not own the stadium but has instituted sustainability elements, including energy-efficient lighting and waste management systems, to minimize its environmental impact.

Retail operations form a significant part of Roma's revenue and sustainability model. The club has several stores throughout Rome that require meticulous logistics planning to balance stock distribution with reducing carbon footprint. Table 1 presents an overview of the various retail locations, the number of employees, and the annual shift capacity, defined as the number of restocking operations carried out using vans with a gross vehicle weight of less than 3.5 tonnes. The analysis included the optimization of delivery routes, distinguishing between supplies directed to central stores, located in Via del Corso, Piazza Colonna, and Via Ottaviano, and those destined for peripheral stores located within shopping centers.

Roma's fleet management is another priority area in reducing its carbon footprint. The club has 78 vehicles in operation across various departments. Table 2 provides a breakdown of the number of vehicles by fuel type.

Regarding travel logistics, the club consider to integrating gradually low-emission vehicles and fuels into its operations to reduce environmental impact. The predominant modes of transportation in away matches vary according to the specific needs of each team. The men's first team primarily uses charter flights for international and domestic matches. High-speed trains are used only for selected destinations where security requirements can be met, while private buses are chosen exclusively for nearby fixtures. The women's and youth teams primarily use private bus services for domestic travels, and commercial flights for international trips.

2.2. Data collection

The data collection process is a complex challenge that requires significant time and resources due to the variety of emission sources and users. In addition, the data may not be accessible or quantifiable and may vary widely depending on the sports season. The variability underscores the importance of data collection for the accurate calculation

Table 1
Operational details of as Roma stores.

Store Location	Employees	Annual Shift Capacity
Via del Corso	18	450
Piazza Colonna	13	320
Via Ottaviano	11	294
C/C Porta di Roma	10	180
C/C Da Vinci	10	220
C/C Maximo	10	200
Stadio Olimpico	Rotational	Matchday Only

Table 2
Corporate vehicle description.

Vehicle Type	Quantity
Diesel Vehicles	9
Electric Vehicles	6
Hybrid/Petrol Vehicles	62

of CCF and highlights some critical issues in the calculation of sustainability goals. Indeed, the improvement of the results obtained by a sports company leads to an increase in emissions under equal conditions. Positive sporting results lead to participation in a greater number of competitions and matches, often including international events, and attract a larger fan base. This translates into increased travel for both the team and the fans, as well as intensified logistical and operational activities, ultimately leading to a higher overall environmental impact. Therefore, in addition to consumption data, data related to the performance of the sports company are also included in the data collection. In detail, a bottom-up approach is used to identify the minimum necessary input data based on the desired output data. The input data are collected from receipts, invoices, employees of the sports company, through questionnaires, or, when not available, reconstructed from the scientific literature through comparison with similar case studies. Therefore, the objective of this phase is both to collect the input data for the calculation of emissions and to develop questionnaires and templates to structure the analysis and facilitate monitoring operations. Within the organizational boundary defined for this study, Scope 3 emissions were estimated for Categories 1, 3, 4, 5, 6, and 7, as these categories represent the main operational drivers and are supported by adequate data sets. The following Scope 3 categories were discarded on boundary and data grounds: Category 2 (Capital goods) and Category 8 (Upstream leased assets) on account of insufficient data on asset level inventory and the requirement for intraannual comparability; Category 9 on account of a lack of data for final customer distribution on the downstream side, particularly for the online sales sector; and Categories 10–15 for lack of primary data support, since these categories are beyond the operational control of the club. Finally, the match-day mobility of fans has been estimated separately under Scope 3 Other and has not been included in the total GHC emissions from operations. In addition, the accuracy of the results also depends on the quality of the underlying activity data and on the robustness of assumptions adopted when direct measurements are not available. Table 3 below describes the data collection methods adopted for the estimation of GHG emission categorized by scope.

Table 3
Data collection details.

Scope	Method of Data Collection
Scope 1: Direct emissions	Direct emissions are estimated using real data as fuel consumption records from on-site combustion sources and company-owned vehicles. For the latter, estimations are based on mileage data derived from maintenance records and the technical specifications of the vehicles.
Scope 2: Indirect emissions from energy	Indirect emissions from energy are estimated using real data obtained from electricity and heating bills.
Scope 3: Category 1: Purchased goods and services	Emissions from acquired goods, such as apparel, catering, and concessions, are estimated by interviews with internal staff and supported by real data.
Scope 3: Category 3: Fuel- and energy-related activities	Emissions from upstream activities related to fuel and electricity purchases, including transmission and distribution losses, were estimated using information provided by internal staff and analyses of comparable case studies.
Scope 3: Category 4: Upstream transportation and distribution	Emissions from shipping goods (e.g., event items) to the organization's premises were estimated based on internal staff interviews regarding shipping methods, frequency, and logistical details depending on the origin of the goods, as well as on real data such as delivery documents.
Scope 3: Category 5: Waste generated in operations	Emissions from waste generated in operations (e.g., training grounds, offices, stadiums) were estimated through interviews with staff to assess the type and amount of waste collected.
Scope 3: Category 6: Business travel and accommodation	Emissions from team and staff travel, including hotel stays, were estimated using invoice data, which allowed for the reconstruction of travel details such as personnel involved, mode of transport, travel distance, and number of hotel nights.
Scope 3: Category 7: Employee commuting	Emissions from daily commuting were estimated based on questionnaires sent to staff and players, assessing both the distance travelled and the extent of remote work.
Scope 3: Other emissions Attendees event mobility	Emissions from home matches mobility were estimated based on questionnaires sent to attendees, assessing both the distance travelled, the origin area and mode of transportation.

2.3. Carbon footprint calculation

The calculation of emissions is carried out by considering activity indicators and emission factors: the former are quantitative measures characteristic of the measured or estimated activity, while the latter, specific to each type of emission source, allow these measures to be converted into quantities of greenhouse gases. Calculation of Carbon Footprint follows global standards for greenhouse gas emissions, namely the Greenhouse Gas Protocol and ISO 14067:2018, Greenhouse gases, Carbon footprint of products, Requirements and guidelines for quantification (International Organization for Standardization (ISO)), which defines internationally standardized principles and requirements for carbon footprint quantification and reporting, and provides for a homogeneous approach to calculating and reporting the emissions on product and organizational scales. A bottom-up approach has been developed in our study, estimating emissions based on individual activities, assets, and organizational units, and then aggregating them to calculate the overall emissions related to the sport season operations. The bottom-up approach has been found eminently suitable for complex sport organizations, as it makes it possible to assign emissions to specific areas and operations.

The generalized calculation method is summarized in the following formula:

$$Emissions\ [kgCO_2eq] = Activity\ Indicator\ [Kg \backslash Km \backslash kWh]\ *\ Emission\ Factor\ \left[\frac{kgCO_2eq}{Kg \backslash Km \backslash kWh}\right] \quad (1)$$

In this study, activity indicators are aggregated over the reference time frame of the assessment, corresponding to the 2023/2024 sporting season, so that the resulting emissions represent season-based totals. The accuracy of calculations is strongly influenced by the quality of emission factors as well as by the reliability, completeness, and representativeness of the activity data used for each emission source; for this reason, those accompanied by transparent methodological documentation are preferred. The CCF calculation of a sports club provides an opportunity to determine the major impact sources, monitor the emission over time and act effectively on sustainability. The calculation considers each subproblem and follows the GHG protocol by allocating emissions among the different scopes 1, 2, and 3. Emissions are calculated by the product of the emission factor and the amount of activity/material. For land, sea and air transport, the Well-to-Wheel (WtW) approach was used to include the emissions associated with the production and distribution of the fuel or energy. WtW defines the accounting boundaries for transport emissions and includes both Tank-To-Wheel (TTW) emissions, generated during vehicle operation, and Well-To-Tank (WTT) emissions, related to fuel/energy extraction, processing and distribution; together, WTT and TTW constitute the overall WtW emissions (Patella et al., 2022). In this paper, spectators' mobility to matchdays is not analyzed in depth within the corporate carbon footprint breakdown; however, for completeness, it can be estimated through the same survey-based procedure adopted for employee commuting, based on origin postcode and transport mode, and reported as a Scope 3 (Other) out-of-scope item. The limitation of the method is the difficulty in finding a detailed and comprehensive database of emission factors. This study attempts to overcome that by relying on values provided by the Department for Environment Food & Rural Affairs (DEFRA) (Department for Environment and F.& R.A. (DEFRA), 2023), which offers a very detailed database (Greenhouse Gas Reporting, 2025). The formulas used in the emission calculation of each impact category concerning the subproblems identified above are shown in Table S4.

2.3.1. Scope 1

Emissions resulting from the consumption of fossil fuels fall under Scope 1 and include the on-site use of such fuels by both mobile and stationary sources owned by the company. Mobile sources primarily consist of company-owned vehicles, while stationary sources include equipment used for industrial processes and heating systems. Emissions from stationary sources are calculated based on the amount of fuel consumed, with distinctions made among different fuel types such as natural gas, gasoline, and diesel. Emissions from mobile sources are estimated according to the distance travelled, vehicle category, and type of fuel used. Vehicles are classified into motorbikes, passenger cars, trucks, vans, and buses, and further categorized by fuel type: gasoline, diesel, compressed natural gas (CNG), liquefied petroleum gas (LPG), and hybrid systems.

2.3.2. Scope 2

Emissions associated with the purchase of steam, electricity, and heating fall under Scope 2. In this context, energy is generated by an external provider and subsequently purchased and consumed by the company, resulting in indirect emissions. The magnitude of these emissions depends on the energy mix of the supplier, which can vary significantly by geographic region. Scope 2 also includes emissions resulting from the charging of the company-owned vehicle fleet. When charging stations are connected to the company's facilities, it is essential to accurately quantify the electricity consumption specifically attributable to vehicle charging, in order to ensure proper allocation of emissions and avoid double accounting.

2.3.3. Scope 3

Emissions associated with the upstream life cycle of purchased goods and services fall under Scope 3, Category 1, and include various operational domains such as water use, food and beverage consumption, and merchandising activities. Water-related emissions are generated by the energy-intensive processes of extraction, treatment, and distribution. It is important to account for water consumption across company operations, facilities, and sponsored activities, as these processes can significantly influence the overall carbon footprint. Similarly, the consumption of food and beverages by employees and customers contributes to emissions through upstream activities such as sourcing, packaging, transport, and waste management. Distinctions are made between products served within company premises, at corporate-sponsored events, and during sporting events. Merchandising activities also represent a relevant emission source, primarily due to the production and distribution of items such as apparel, accessories, and memorabilia. Key contributors include raw material extraction, manufacturing processes, and logistics.

Emissions from sporting or corporate event consumption of energy fall within Scope 3, Category 3. The emission is generated by electricity, heating, or cooling consumed by sporting or corporate events. The category is distinct from business-as-usual building power consumption by specifically including temporary intense consumption by big crowds of people. The estimation takes into account utility bills, temporary power facilities, and historical consumption of power by comparable events. Emissions from generated waste fall under Scope 3, Category 5. The category is composed of emissions that result from collecting, transporting, and disposing of waste generated on company-owned properties. The mode of disposal, mode of transportation, and type of waste determine overall emission levels. The mode of handling waste such as landfilling, incineration, composting, and recycling each have unique emission factors.

Emissions from logistics fall within Scope 3, Category 4, including upstream logistic, that entail procurement of supplies and goods, whereas downstream logistics involve product delivery to customers. The emission is segmented by vehicle category, mode of movement (road, train, ship, airplane), distance travelled, and goods' conveyed weight.

Emissions from business travel fall under Scope 3, Category 6. These emissions are generated by air, rail, and road transportation, as well as by employees' overnight stays. The calculation methodology distinguishes between business and personal travel, taking into account vehicle category and fuel type as key variables in the estimation process. Emissions from accommodation, resulting from hotel stays by employees, athletes, and event participants, are calculated based on the type of accommodation and the country of stay, while also considering the energy efficiency level of the facility and the local energy mix.

Emissions from employees' commute fall under Scope 3, Category 7. The emissions are produced by daily trips home to work. The private vehicle, transit, cycling, and on foot modes of transit have varied emission levels. The sources of data are employees' questionnaire answers and transit pattern observation. Given its relevance, the emissions associated with spectators' mobility to attend home and away sporting events can be estimated; in this study, the mobility to attend sporting event is treated as a Scope 3 (Other) item and reported separately.

Table 4 identifies the categories analyzed for each asset, with Scope 1 limited to the Fulvio Bernardini Sports Center (corporate vehicles, refrigerants, and fuels), Scope 2 energy accounted for in the fixed assets (Stores, Tolstoy Avenue, and Fulvio Bernardini Sports Center), and Scope 3 mapped asset-by-asset (matchday-related items at Stadio Olimpico; business travel and accommodation for Away Matches; marketing-related items, water and waste streams for Stores and Tolstoy Avenue; and employee commuting for Tolstoy Avenue and Fulvio Bernardini Sports Center).In this study, refrigerant use refers to the refrigerant gases used for charging and maintenance of air conditioning and cooling systems operated within the club's facilities.

The status of various categories has been shown in Table 4 using unchecked boxes to identify the different conditions. There are some categories which have been classified as inapplicable for a particular asset, which basically means that the activity related to the category does not pertain to the particular context. There have been some situations in which some categories have been deliberately avoided in certain assets. This has been a strategy or approach followed to make it possible to have a certain level of comparability between the results

Table 4
Mapping emission sources across organizational activities and Locations.

	Internal Organisation		Stadium		Training Facilities
Scope	Stores	Tolstoy Avenue	Stadio Olimpico	Away Matches	Fulvio Bernardini Sports Center
Scope 1					
Corporate Vehicles					✓
Refrigerants					✓
Fuels					✓
Scope 2					
Energy	✓	✓			✓
Scope 3: Category 1					
Food and drinks			✓		
Marketing	✓				
Marketing charity	✓				
Marketing waste	✓				
Water	✓	✓	✓		✓
Scope 3: Category 3					
Energy Events			✓		
Scope 3: Category 4					
Marketing transportation	✓				
Scope 3: Category 5					
Glass Waste	✓	✓			✓
Non-Recyclable Waste	✓	✓	✓		✓
Organic Waste					✓
Paper Waste	✓	✓			✓
Plastic Waste	✓	✓			✓
Scope 3: Category 6					
Accommodation				✓	
Transportation				✓	
Scope 3: Category 7					
Employee Commuting		✓			✓

Table 5
Carbon emissions breakdown by scope (TCO_2e and percentage).

Scope	tCO_2e	Percentage
Scope 1	654	9.5%
Scope 2	527	7.7%
Scope 3	5675	82.8%
Total	**6856**	**100%**

related to the Carbon Footprint year after year. There have been some conditions in which the results have been avoided for certain assets simply because there have been no comparable data.

3. Results

The total Corporate Carbon Footprint of the sport organization for the 2023/2024 resulted in 6857 tCO_2e. These emissions, considering the GHG Protocol, were divided into three scopes of classification: Scope 1 and Scope 2, and Scope 3 (Table 5 and Fig. 2) and by location and internal division, Fig. 3.

In addition, spectators' mobility to home matchdays over the season was estimated at 10,825 tCO_2e, corresponding to 64,138,401 km travelled and an average of 401 tCO_2e per home match. Car travel represented the main transport mode, accounting for 51.92% of spectator mobility to home matches (including both drivers and passengers), followed by motorcycles (41.30%) and public transport (6.17%), while all other modes were marginal. Given the magnitude and

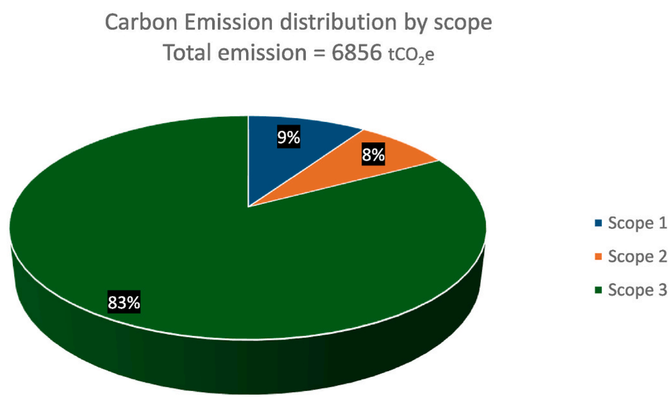

Fig. 2. Carbon emission distribution by scope.

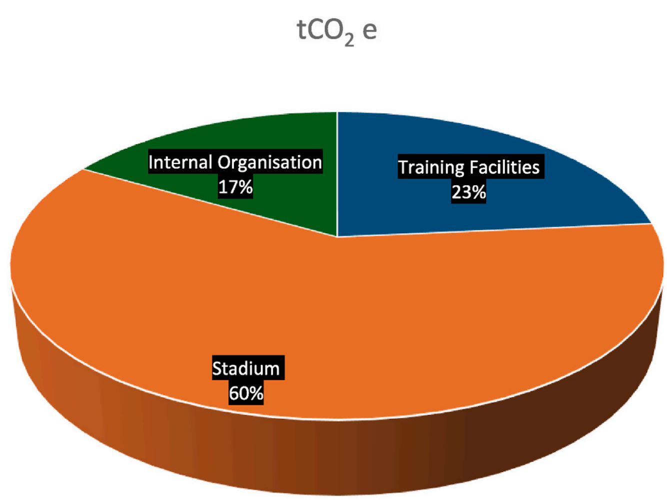

Fig. 3. Pie Chart of Carbon Emissions divided by Location and Internal Division (Percentage).

Table 6
Scope 3 carbon emissions breakdown by category (TCO$_2$e, percentage of total CCF, and percentage of scope 3).

Scope 3	tCO$_2$e	% of totale CCF	% of Scope 3
Category 1	1817	26.5%	32%
Category 3	157	2.3%	2.8%
Category 4	86	1.3%	1.5%
Category 5	113	1.6%	2%
Category 6	2847	41.5%	50.2%
Category 7	655	9.6%	11.5%
Total	**5675**	**82.8%**	**100%**

methodological specificity of spectator travel emissions, this component is reported separately for completeness under Scope 3 (Other), and is addressed in dedicated work focused on mobility impacts. The dominance of Scope 3 emissions (detailed in Table 6) indicates the challenge in controlling environmental effects from indirect operations, such as transportation, water use, and waste generated.

For Scope 1, they are caused by corporate vehicles, fuel and refrigerant use. The refrigerant volume alone accounted for 279 tCO$_2$e, highlighting its significant contribution to direct emissions and the need for strict monitoring and control. Corporate vehicles contributed 207 tCO$_2$e, which indicates the extent of internal logistics and travel for operations. Finally, fuels contributed 169 tCO$_2$e. Scope 2 involves the emissions resulting from purchased energy by facilities, training centers, offices, stores, among others. It represented 527 tCO$_2$e and 7.7% of the overall footprint.

Table 6 shows the percentage contribution of each category to Scope 3. There, Category 6, Travel and Lodging is the largest contributor, at 50% of Scope 3 emissions and 41.5% in total. It involves the overall transportation and accommodation of all the teams participating in different matches and events. That simply means that much is at stake for travel emissions. The other large contributors are Category 1: Goods and Services, at about 32%, and Category 7: Employee Commuting, at 11.5%. The indirect emissions are embodied in the consumption of materials and transportation of the employees to the workplace.

More granularity is seen in the split of emissions by organizational department, where the greatest contribution is made by stadium operations: home and away matches that represent almost 60% of the total footprint. The second largest contribution, 23.6%, comes from training facilities, with stores adding 11.8% and offices 4.8%.

4. Discussion

4.1. Overall carbon footprint and scope distribution

Fig. 4 shows how carbon emissions by scope are divided into the different corporate assets.

With a comparative analysis of greenhouse gas emissions (CO$_2$e) in the various operating facilities of a sports club divided between the indoor organization, stadium, and training facilities, one is immediately struck by enormous differences in contributions by category and variation in environmental footprint. Identification of priority areas and opportunities for change can be obtained by comparing different sources of emission with their operating characteristics.

One thing that stands out is the dominance of the stadium as a major source of emissions, with a contribution of 59.9%. This result seems to be particularly notable, considering the number of events organized annually is comparatively low, while training facilities operating 365 days per year contribute no more than 23.6% of the total emissions. In the meantime, the contribution of internal organization is not so significant, at the level of 16.6% percent, although there are certain critical categories within this cluster, including marketing and water consumption.

Transportation is the front-runner as the major contributor to emissions, with a share of 40.7% of the total. Within this sector, transport related to stadium events is the most contributing element. Emissions from team travel and logistics (2793 tCO$_2$e) are far greater than those generated from commuting by other facility staff. Even so, the training facilities' contribution is far greater than 518 tCO$_2$e compared to the indoor organization 137 tCO$_2$e, pointing to the greater consumption of private transport by the staff of the former. Energy consumption is another important contributor (526 tCO$_2$e) divided largely between training facilities and the stadium.

The former demonstrates a continuous but proportional impact with 126 tCO$_2$e for their current activity, while the stadium, with a limited use (typically only 30 days per year), yields 400 tCO$_2$e - i.e., a more concentrated but intensive usage. This disparity is added to by the energy event category, which provides an extra 157 tCO$_2$e for specific activities in the stadium's case. These two complexes differ in that the stadium is an ideally appropriate location for energy efficiency initiatives, while operational streamlining would reduce current energy consumption in training complexes. Food and beverage emissions are another primary consideration, with almost all concentrated in the stadium at 976 tCO$_2$e.

This production, transport, and preparation category underlines the strength of these events in GHG emissions terms. Although absent as an entry in the other facilities, this relative importance from the overall total (14.2% percent) does emphasize the importance of sustainable alternatives within the current model of food supply, both by increasing vegetarian alternatives and by introducing local producers. Catering is thus a specific focus of sports event management.

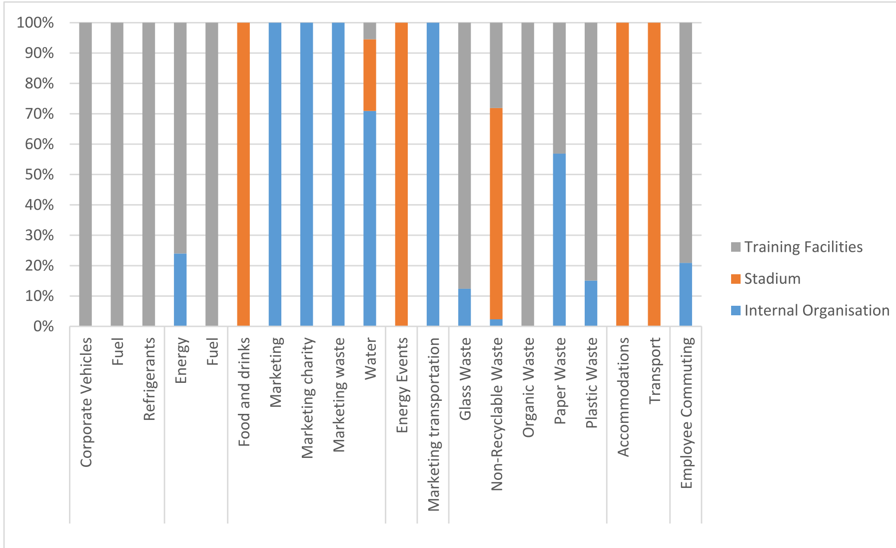

Fig. 4. Carbon emissions distribution by scope, location, and category.

Another insightful observation is provided by the study of waste. Non-recyclable stadium waste is over twice the one from training facilities, respectively 76 tCO_2e and 31 tCO_2e, even though the stadium operates on a much lower number of operating days. The difference is due to less environmentally friendly management of events - each event results in a much larger amount of disposables and meals. Training facilities, on the other hand, are operated daily but with less proportional waste, as the majority impact is displayed during the event duration period itself. Internal organization, while having a lower percentage in the total count, displays some important points. Marketing is 557 tCO_2e and is prominent due to the vast production and distribution of promotion materials. This sector can be greatly optimized by a shift to digital communications with less reliance on print and logistics. Water consumption at 137 tCO_2e also has room for optimization such as the implementation of more efficient systems and water-conserving awareness campaigns.

Facilities comparison shows some intriguing dynamics: the stadium is the central point of strategic initiatives, i.e., those on which most strategic initiatives would have a very strong and disproportional impact, while the training facilities are much more impactful overall operational effectiveness but still contain key points like refrigerants and commuting. Internal organization has a dispersed impact with low value; there is some potential in some categories like marketing.

4.2. Role of matchday operations and spectator-related emissions

By only considering home games, which account for about 18.3% of the club's yearly emissions as shown in Table 7, the calculated carbon footprint of a single sporting event is 46.5 tCO_2e.

This total annual attendance estimate of around 1.7 million spectators equates to an estimated 2.4 kg CO_2e per spectator. However, this relatively low number is largely due to the calculation not including the emission from transport. By comparison, most other analyses have included the transport emission, and their attendee-based estimates are significantly higher. When considering the out-of-scope estimate of spectators' mobility to home matchdays, travel-related emissions amount to 401 tCO_2e per home match (10,825 tCO_2e over the season), corresponding to 6.46 kg CO_2e per spectator; this confirms that spectator travel can dominate the overall event-related footprint when an extended boundary is adopted. For the Bundesliga, for example, the average emission per spectator per game is 27.8 tCO_2e a game, of which 70% is attributable to fan transport. Meanwhile, Rapid Vienna totaled 99,5 tCO_2e as total emissions per game and thus was 6.0 $kgCO_2e$ per spectator: public transport contributes 27.1% of all the figures of emissions generated (Herold et al., 2024). Discussion of the University of Tennessee's football seasons, their findings were at 154,717 tCO_2e over four seasons with emissions per home match ranging between 4719.9 and 6947.5 t CO_2e, corresponding to approximately 6.1 kg CO_2e per match and fan, whereby transportation contributes 57% of participation (Cooper, 2020). In another study (Liu and Guo, 2023), authors estimated fan contribution of 8–15 $kgCO_2e$ per event while local football games are reported at 3.5 $kgCO_2e$ from spectators. In all such studies, fan transport appears to be assigned large shares; proportionately, its emissions grow with the number of spectators as well. There is tremendous variation in the CCF values according to the level and geographical contexts of this study when considering the sport category.

As for energy use (McCullough et al., 2023) entifies that energy use in stalls for lighting and heating within the stadium is responsible for 55% of the emissions.

Other research (Liu and Guo, 2023) also provide similar results, where stadiums account for energy consumption, around 20–30% of the emissions. Energy consumption is around 13% in one game of AS Roma's emissions and 2% of all the annual emissions of the club. Slightly less in comparison with other findings, such a percentage results in the estimation of average annual energy consumption in medium-sized football stadiums to be around 25,000 kWh per infrastructure. However, other research (Cooper, 2020), refers to energy consumption between 10% and 30%, based on specific conditions. In AS Roma, the emissions footprint is different in hospitality; food and beverage provide 78% of the event's emissions. That is a plausible estimate for about 0.6 kg food/beverage per spectator per event and 36.15 tCO_2e for one event. It was estimated to be around 39.5 tCO_2e for an average sport match in a research (Uusitalo et al., 2024). This has been estimated to be a total of

Table 7
Carbon Emissions Breakdown for Home Matches (based on 27 home matches in the 2023/2024 season).

Home Matches	tCO_2e	Percentage compared to home matches
Scope 3: Category 1	1021	81.4%
Food and drinks	976	77.8%
Water	45	3.6%
Scope 3: Category 3	157	12.5%
Energy Events	157	12.5%
Scope 3: Category 5	76	6.1%
Non-Recyclable Waste	76	6.1%
Total	1254	100%

Table 8
Carbon footprint comparison for as Roma (tCO2e) based on various metrics.

AS Roma – 6856,82 tCO_2e		CCF (tCO_2e)
Employee	408	17
Revenue	277.1 Mln €	0.025 $kgCO_2e$
Spectators	1,700,000	4.03 $kgCO_2e$
Matches	54	127
Goals	90	76
Points	91	75
Home Matches	27	254

35 tCO_2e event CO_2e for an average match, contributed by meat product sources around 40% and beverages representing another 35% (McCullough et al., 2023; McCullough and Trail, 2023).

4.3. Key emission drivers across club assets

Analysis through CCF underlines the environmental impact related to various organizational and sporting dimensions of AS Roma. With a total CCF estimated at 6856 tCO_2e, this converts approximately into 2.5 g of CO_2e every euro of revenue, highlighting how much the financial activity costs to the environment (Table 8).

When considering the workforce, this gives 17 tCO_2e per employee per year, reflecting the organizational and operational intensity required to maintain a professional sports club.

From a match-centric perspective, the analysis shows that in the course of the season, AS Roma have played an average of 54 matches, assuming a carbon footprint per game of 127 tCO_2e, while home matches were substantially higher, at 255 tCO_2e per match, considering a higher stadium-related activity and presence of fans.

This means that, from a performance viewpoint, sporting achievement has reached a new dimension: each goal scored by AS Roma corresponds to 76 tCO_2e, while each league point gained reflects 75 tCO_2e, quantifying how much every success on the field weighs in environmental terms. These metrics have provided a grounding through which to understand the environmental impacts of the club across multidimensional organizational and sporting perspectives, with the objective of developing targeted sustainability strategies surrounding revenue generation, match operations, and performance.

Whereas the management practices influence the formulation of the sustainability strategies, the research will specifically focus on the measurement of the Corporate Carbon Footprint that results from the operations of the corporation without delving deeper into the management practices.

This research uses an organized and bottom-up based method that conforms to international standards of carbon accounting to improve the accuracy and quality of carbon footprint assessments in sports bodies. The approach will help sports bodies draw clear boundaries of emissions in complex systems and allows for the establishment of standards that sports bodies will follow to improve emissions assessments.

4.4. Limitations of the research and future developments

The present research is a prelude to academics and practitioners alike with a comprehensive study consolidated from a broad area of operation and one of the largest sporting organizations of the world. However, there are certain segments that should be dealt with and updated further.

One of the main limitations is the monitoring of food intake. Food concessions in stadium curves, daily intakes in training camps, and food intake during team and staff travel are not monitored yet. Energy use figures for the stadium currently depend on generalized averages; the possibility of more precise measurement would increase the validity of the analysis.

Another important topic needing an analysis is the environmental effect of online product sales. In the research carried out in the previous years, the environmental effect of the shipment of orders from stores or warehouses to the ultimate customer in the case of online shopping has not been taken into account. Face-to-face selling has been debated up to now.

Further areas for development could be a follow-up research on the environmental impact of an entire team's youth games, not only away games but also home games, to give an overall picture. These extensions would greatly enhance their sustainability efforts and further enhance the relevance and quality of the research findings.

For completeness, also the carbon emissions from fan mobility were estimated, for the reason that transportation of spectators contributes a significant source of carbon emissions. The contribution of transportation of spectators from the single event, with 62,000 spectators on average, translates into 401 tCO_2e, equal to an average of 6.46 kg of CO_2e for every single spectator per event. However, the attribution of these emissions raises methodological challenges, as spectator travel may be considered both part of individual carbon footprints and influenced by sport organizations. Although these emissions lie partly outside the direct operational control of the club, sport organizations may still play an important role in influencing mobility choices through infrastructure planning, communication strategies and mobility management policies. Given the complexity of this issue, it will be addressed in a dedicated future study.

Mitigation strategies for all categories and levels have been undertaken, and significant efforts have been made towards lowering various categories of emissions. But with the complexity of efforts for lowering different categories of emissions, more accurate study of mitigation policies and their effectiveness will be conducted in future research.

Among the strongest points for action, transportation of spectators has been identified as a key point for lowering emissions. Implementing policies for low-carbon mobility solutions, such as incentives for the use of public transit, ride-share systems, and improved cycling and on-foot access for spectators, could lower the carbon footprint of sporting events significantly. Future research will explore potential policies and their effectiveness in reducing the ecological footprint of spectators' transportation.

5. Conclusion

The current investigation provides a detailed analysis of the Corporate Carbon Footprint given a professional football club, focusing on the identification of emissions from the main operational areas, namely ground operations, training grounds, and organizational operations. In drawing the organizational boundary, the transport activities associated with match-day mobility of fans have been categorized as a Scope 3 (Other) source and thus are not taken into account in calculating the CCF percentages.

The overall value for CCF in the 2023–2024 year is 6856 tCO2e, with Scope 3 emissions accounting for the largest share (82.8%) of overall emissions, largely due to team travel, purchasing of goods and services, and employee commute emissions. In terms of operational categories, stadium operation is identified as a dominant emission sector (59.8%), followed by training facilities (23.6%) and then internal operations (16.6%). In a separate calculation to cover fans' mobility to home matches, Scope 3 (Other) emissions were calculated to be 10,825 tCO2e, or about 1.6 times higher than the boundary-footprint calculations provided in this submission.

From an event perspective, one domestic fixture emits 46.47 tCO_2e, whereas adding estimated audience travel-related emissions raises this to around 447 tCO_2e per fixture. Such results emphasize how significant are the environmental concerns linked to professional sport and how important are indirectly related emissions that occur outside of the control of sporting clubs.

In addition to indirect emissions, sport organizations can also act directly on operational sources within Scope 1 and Scope 2. As discussed in the analysis of operational drivers, potential mitigation measures include electrification of the corporate vehicle fleet, transition to renewable electricity suppliers, and improved management of energy use in training facilities, particularly lighting systems. For example, full fleet electrification could reduce total emissions by approximately 157.9 tCO_2e (about 2.3% of total emissions), subject to economic and operational feasibility. While these measures contribute to operational decarbonization, Scope 1 and Scope 2 represent a relatively limited share of total emissions, and the greatest mitigation potential remains associated with Scope 3 sources.For purposes of comparison, total corporate carbon footprint estimated for the 2023/2024 season (6856 tCO_2e) may be compared to the annual carbon sequestration capacity of natural ecosystems. Using an average sequestration of about 4 tCO_2e per hectare per year for a temperate forest ecosystem typical of central Italy, as estimated in IPCC studies (IPCC. AR6 Working Group III – Mitigation of Climate Change, 2022), it means that an annual carbon footprint of the club translates to an area of approximately 1700 ha of forest sequestrating carbon. The comparison provided above serves only as an illustrative tool to assist in understanding the scale of carbon emissions.

The case study football club is a complex organization with a large number of staff in excess of 400 workers. The organization has a 70,000-seating capacity stadium. In addition to the football club's organizational complexity in terms of the number of workers and the infrastructure put in place, the club organizes a high number of matches. The club's activities are not only limited to the two professional football teams but the organization's football programs are multilayered. Over 300 matches are played within a given calendar year. Methodologies in the study are applicable to similar football clubs.

CRediT authorship contribution statement

Dante Maria Gandola: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Dario Ballarano:** Writing – original draft, Software, Resources, Methodology, Data curation. **Sergio Maria Patella:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Francesco Asdrubali:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization.

Informed consent statement

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2026.100415.

Data availability

Data will be made available on request.

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