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The current state of carbon footprint quantification and tracking in the agri-food industry

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ABSTRACT

The agri-food sector is a major contributor to greenhouse gas (GHG) emissions, accounting for approximately 30% of global energy consumption and a substantial share of CO_2, CH_4, and N_2O emissions. As global food systems transition toward sustainability, carbon footprint quantification has become critical for reducing environmental impacts and achieving carbon neutrality goals aligned with the European Green Deal. This paper provides a comprehensive review of methodologies for carbon footprint assessment, including the GHG Protocol – Product Standard, ISO 14064, ISO 14067, Life Cycle Assessment (LCA), and PAS 2050, and their applications in food production systems. A case study on the wheat-to-bread supply chain illustrates the practical application of these frameworks in carbon footprint calculation. The study explores key challenges in carbon footprint tracking, such as data availability and quality issues, complexity of global supply chains, standardization gaps, and financial constraints for small and medium-sized enterprises (SMEs). It further highlights emerging digital technologies, including artificial intelligence (AI), blockchain, and IoT sensors, which enhance emission monitoring, optimize agricultural inputs, and improve transparency in food supply chains. Additionally, the study examines the role of policy frameworks, particularly EU regulations, and the impact of consumer behavior on sustainable food choices. Findings indicate that livestock and fisheries remain the highest-emitting subsectors, while plant-based foods have significantly lower carbon footprints. Integrating digital solutions, standardized methodologies, and regulatory incentives is crucial for improving carbon accounting accuracy and accelerating decarbonization efforts. The paper concludes with recommendations for policymakers, industry stakeholders, and researchers, emphasizing harmonized reporting frameworks, improved access to open carbon databases, and investment in climate-smart agriculture. Strengthening consumer engagement and implementing eco-labeling strategies can further drive demand for low-carbon food products, supporting the transition toward a sustainable and climate-resilient food system.

Keywords: carbon footprint, food industry, GHG Protocol, ISO 14064, sustainable food production, decarbonization

INTRODUCTION

Climate change poses a significant challenge to global sustainability, particularly within the agri-food sector, a major contributor to greenhouse gas (GHG) emissions. The industry accounts for approximately 30% of global energy consumption and a substantial share of CO_2, CH_4, and N_2O emissions, making its decarbonization essential in mitigating environmental impacts **[1]**. Food production systems contribute to climate change, biodiversity loss, and land degradation, necessitating comprehensive strategies to reduce emissions **[2]**. Monitoring and quantifying the carbon footprint in the agri-food sector is, therefore, a crucial step in achieving carbon neutrality goals in line with the European Green Deal.

Carbon footprint (CF) represents the total amount of greenhouse gas (GHG) emissions, expressed in CO_2 equivalents (CO_2e), associated with a product, process, or organization throughout its lifecycle. The quantification of CF can be performed using different methodological frameworks:

- ISO 14067:2018 focuses on the product's carbon footprint, integrating life cycle assessment (LCA) principles.
- GHG Protocol provides corporate and product-level standards, emphasizing supply chain-wide emissions reporting.
- PAS 2050 offers a simplified approach to product carbon footprinting, mainly used in the UK.

A standardized methodology for assessing and managing the carbon footprint of agricultural and food products is essential for achieving effective decarbonization. The GHG Protocol – product life cycle accounting and reporting standard **[3]** provides a structured framework for organizations to measure and report emissions associated with their products across their life cycle. Additionally, ISO 14064 **[4]** and ISO 14067 **[5]** enable the quantification of emissions at various supply chain stages, promoting transparency and data-driven decision-making for emission reductions. A widely used complementary approach is Life Cycle Assessment (LCA), which evaluates the environmental impact of products throughout their life cycle. However, its application in policy and industry must be carefully managed to prevent misleading conclusions regarding climate mitigation **[6]**.

Despite the availability of robust methodologies, implementing carbon inventories in the agri-food sector faces several challenges. Key barriers include data availability and quality, inconsistencies in emission factors, and the complexity of supply chains involving multiple stakeholders **[7]**. Economic constraints also play a significant role, as small and medium-sized enterprises (SMEs) often lack the financial resources and expertise to conduct comprehensive carbon footprint assessments **[8]**. Furthermore, fragmented regulatory frameworks and a lack of enforcement hinder the adoption of carbon footprinting across the industry **[9]**.

At the same time, climate change is accelerating due to the rising atmospheric concentrations of GHGs, such as CO_2, CH_4, and N_2O, which result from rapid industrialization, deforestation, and fossil fuel combustion **[10]**, and **[11]**. The Intergovernmental Panel on Climate Change (IPCC) projects that CO_2 levels in the Earth's atmosphere could double by 2100, potentially leading to a global temperature rise of up to 6°C above pre-industrial levels **[12]**. These climatic shifts significantly impact agroecosystems, particularly horticultural and food crop production, where environmental stressors – such as heatwaves, UV radiation, drought, and soil degradation – are becoming increasingly common **[13]**.

Plant growth's physiological processes, including photosynthesis, respiration, nutrient uptake, and water retention, depend heavily on climate conditions **[14]**. Elevated temperatures and erratic precipitation patterns can result in lower crop yields, reduced fruit quality, and increased susceptibility to pests and diseases. Moreover, shifting climate patterns have led to longer growing seasons in some regions but harsher conditions in others, affecting agricultural productivity and food security **[15]**, and **[16]**.

To overcome these challenges, emerging technologies and innovative tools are being developed to enhance carbon footprint monitoring and reduction in the agri-food sector. Digital solutions such as blockchain technology for transparent data tracking, artificial intelligence for predictive analytics, and IoT-based monitoring systems are improving the accuracy and efficiency of carbon footprint assessments **[17]**. In addition, incentive-driven policies and integrating carbon footprint tracking into corporate sustainability strategies can drive greater adoption of these methodologies **[18]**.

This review provides a comprehensive overview of current methodological approaches for carbon footprint quantification in the agri-food sector, focusing on the GHG Protocol – product standard, ISO 14064, and Life cycle assessment (LCA). Furthermore, it explores the significant challenges associated with implementing carbon inventories and discusses potential strategies and technologies that can facilitate more efficient carbon footprint monitoring and reduction. Recommendations for improving regulatory frameworks, data transparency, and stakeholder collaboration are presented to support the transition toward sustainable and low-carbon food production systems.

Given the agri-food sector's significant contribution to global greenhouse gas emissions, it is essential to analyze the different stages of the food supply chain and their impact on climate change. To illustrate the scale of these emissions and their distribution within the food system, the following figure (Figure 1) presents the main sources of greenhouse gas emissions across the global food supply chain **[1].**

Figure 1 illustrates the contribution of the food supply chain to global greenhouse gas emissions, accounting for 26% of total emissions, while the remaining 74% comes from non-food sectors. The emissions are divided into four key categories: supply chain (18%), livestock & fisheries (31%), crop production (27%), and land use (24%), with livestock and fisheries being the largest contributors due to methane emissions, manure management, and fuel use in fisheries. Crop production and land use also significantly impact emissions, mainly through land-use changes and soil cultivation **[1]**.

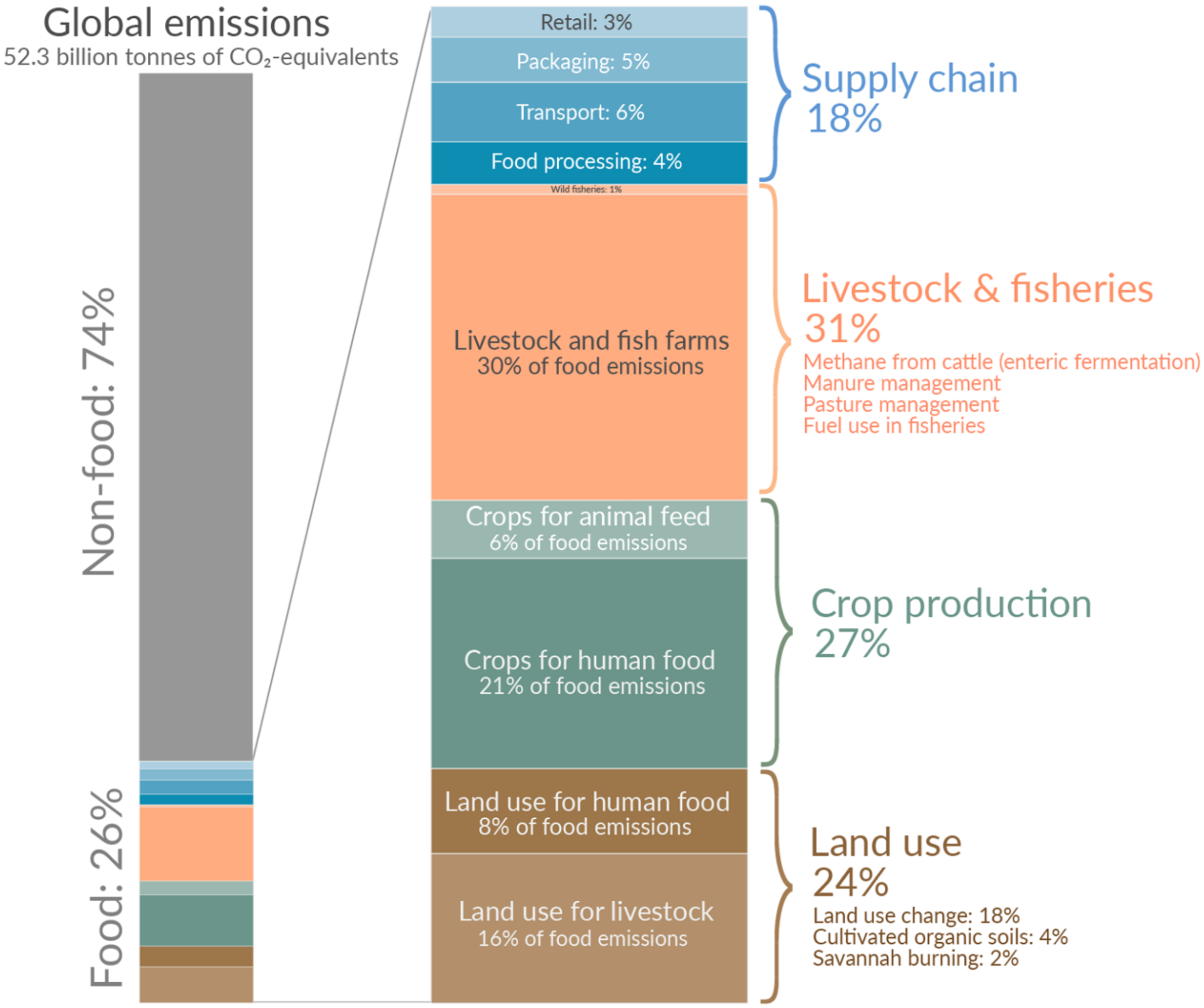

Figure 1 Global greenhouse gas emissions from the food supply chain.

Carbon footprint of basic food categories

The environmental impact of food is increasingly analyzed in terms of its carbon footprint (CO_2e), which represents the total emissions of carbon dioxide equivalents generated throughout its life cycle—from raw material production, processing, packaging, and transportation to retail. Foods with high carbon footprints significantly contribute to climate change, and reducing their consumption can be a key factor in developing sustainable food systems.

Based on data from Den Store Klimadatabase, the following table presents key food categories and their average carbon footprint measured in kilograms of CO_2 equivalents per kilogram of food (kg CO_2e/kg).

Table 1 Carbon Footprint of Selected Basic Food Categories.

Category	Food Item	CO_2e / kg
Meat and Poultry	Beef	21.79
	Pork	3.29
	Chicken	2.84
	Lamb	23.98
	Ground beef	26.61
Fish and Seafood	Farmed salmon	4.15
	Tuna	6.10
	Farmed shrimp	19.00
Dairy and Eggs	Milk, 1.5% fat	1.19
	Whole milk	1.37
	Semi-hard cheese	8.52
	Natural yogurt	2.20
	Eggs	1.60
Grains and Cereal Products	Wheat bread	0.94
	Dry pasta	1.24
	Oat flakes	0.92
	White rice	4.45
Legumes and Nuts	Lentils	0.71
	Beans	0.75
	Chickpeas	0.79
	Hazelnuts	2.30
Fruits and Fruit Products	Apples	0.44
	Bananas	0.81
	Oranges	0.94
	Grapes	1.10
Vegetables and Vegetable Products	Potatoes	0.20
	Carrots	0.16
	Tomatoes	1.10
	Lettuce	0.69
Oils and Fats	Sunflower oil	3.29
	Olive oil	4.92
	Butter	9.64

Note: **[19]**

The data indicate that animal-based foods, particularly red meat, have the highest carbon footprints. Beef (21.79 kg CO_2e/kg), lamb (23.98 kg CO_2e/kg), and ground beef (26.61 kg CO_2e/kg) exhibit the most significant environmental impact due to high water and feed consumption during livestock farming as well as methane emissions from ruminant digestion.

Conversely, plant-based foods like fruits, vegetables, grains, and legumes have significantly lower emissions. Legumes like lentils (0.71 kg CO_2e/kg) and beans (0.75 kg CO_2e/kg) are among the most environmentally friendly protein sources. Among grains, white rice (4.45 kg CO_2e/kg) has a relatively high footprint, mainly due to methane emissions from flooded rice paddies.

Dairy products and eggs have a moderate environmental impact—for example, cheese (8.52 kg CO_2e/kg) has a higher carbon footprint than pork or chicken due to the large volume of milk required for cheese production. Eggs (1.60 kg CO_2e/kg) have a lower footprint than most animal-based foods but still exceed that of many plant-based options.

The category of oils and fats shows that animal-based fats, such as butter (9.64 kg CO_2e/kg), have a higher carbon footprint than plant-based oils. Olive oil (4.92 kg CO_2e/kg) is more resource-intensive than sunflower oil (3.29 kg CO_2e/kg), reflecting differences in agricultural and processing methods.

These findings suggest that shifting towards plant-based diets or at least reducing the consumption of red meat and animal products can significantly lower an individual's carbon footprint. Additionally, food production systems' efficiency, origin, and processing methods are crucial in determining overall emissions **[19]**.

Methodology: Frameworks for carbon footprint quantification

The carbon footprint quantification in the agri-food sector relies on internationally recognized standards and methodological frameworks. These methodologies provide systematic approaches for measuring, reporting, and verifying greenhouse gas (GHG) emissions, ensuring industry consistency and comparability. The key frameworks used for carbon footprint assessment are described below.

GHG Protocol – product standard

The carbon footprint of products is an essential parameter for assessing their environmental impact. It represents the total amount of greenhouse gas (GHG) emissions associated with a product throughout its life cycle, from raw material extraction to disposal **[3]**. The GHG Protocol – Product Life Cycle Accounting and Reporting Standard provides a structured and scientifically recognized methodology for quantifying these emissions and ensuring comparability across different products and industries **[9]**.

The methodology follows the Life Cycle Assessment (LCA) framework, which systematically accounts for emissions from various stages of production, distribution, use, and end-of-life treatment. The system boundaries can be cradle-to-gate (from raw material extraction to the factory gate) or cradle-to-grave (including use and disposal). To quantify emissions, activities are categorized into Scope 1 (direct emissions from own operations), Scope 2 (indirect emissions from purchased energy), and Scope 3 (other indirect emissions from supply chain activities) **[9]**.

Methodology for carbon footprint calculation

The quantification of the carbon footprint (CFP) is based on the activity data collected across the product life cycle and multiplied by the corresponding emission factors (EF). The general formula (1) is expressed as follows:

$$\textbf{Total Emissions} = \sum(\mathbf{Ai} \times \mathbf{EFi}) \qquad (1)$$

Where:

- Ai – represents an activity (e.g., fuel consumption, electricity use, fertilizer application, transportation)
- Efi – Is the emission factor for the corresponding activity (kg CO_2e per unit of activity) **[5]**

- This equation (1) forms the foundation of carbon footprint calculations and ensures that emissions from different processes can be consistently assessed. The accuracy of the results depends on the reliability of input data and the selection of appropriate emission factors.

Case study: carbon footprint of wheat-to-bread production

The wheat-to-bread supply chain comprises multiple emission sources, including agricultural production, milling, baking, and transportation. The following calculations illustrate the application of the GHG Protocol – Product Standard in a scientifically rigorous manner.

Emissions from wheat cultivation

The use of fertilizers, fuel for farm machinery, and irrigation energy consumption primarily influences the carbon footprint of wheat production. The key emission sources include:

- Nitrogen-based fertilizers contribute significantly due to N_2O emissions. Assuming an application of 120 kg of fertilizer per hectare and an emission factor of 5.7 kg CO_2e per kg of fertilizer, emissions are calculated as (2):

$$\textbf{Emissions}_{\textbf{fertilizer}}\textbf{=120×5.7=684 kg CO}_2\textbf{e per hectare} \quad (2)$$

The application of synthetic fertilizers represents a significant emission source in crop production, as nitrogen-based fertilizers not only lead to direct CO_2 emissions from their production but also contribute to nitrous oxide (N_2O) emissions, which have a significantly higher global warming potential (GWP).

- Fuel consumption for plowing, sowing, and harvesting is estimated at 50 liters per hectare, with an emission factor of 2.67 kg CO_2e per liter of diesel is calculated as (3):

$$\textbf{Emissions}_{\textbf{diesel}}\textbf{=50×2.67=133.5 kg CO}_2\textbf{e per hectare} \quad (3)$$

Agricultural machinery operations significantly contribute to Scope 1 emissions, and the type of fuel used and its combustion efficiency directly affect the total footprint. Modern precision agriculture techniques may help optimize fuel usage and reduce emissions.

- Irrigation energy consumption depends on water usage. Assuming 500 m^3 of water per hectare and an energy requirement of 0.5 kWh per m^3, with an electricity emission factor of 0.4 kg CO_2e per kWh, the emissions are calculated (4):

$$\textbf{Emissions}_{\textbf{irrigation}}\textbf{=500×0.5×0.4=100 kg CO}_2\textbf{e per hectare} \quad (4)$$

The energy intensity of irrigation largely depends on water source depth, pumping efficiency, and irrigation technique. More sustainable irrigation systems, such as drip irrigation, can reduce energy consumption and thus lower carbon emissions.

- Total emissions from wheat cultivation is calculated as (5):

$$\textbf{684+133.5+100=917.5 kg CO}_2\textbf{e per hectare} \quad (5)$$

Based on an average wheat yield of 4,000 kg per hectare, the carbon footprint per kilogram of wheat is calculated as (6):

$$\textbf{917.5 ÷ 4000 = 0.229 kg CO}_2\textbf{e per kg of wheat} \quad (6)$$

This value represents the baseline emissions associated with wheat production and is an essential benchmark for sustainability improvements in the agricultural sector.

Emissions from wheat milling (flour production)

The milling process converts wheat into flour, requiring 50 kWh of electricity per ton of wheat. The electricity emission factor is 0.4 kg CO_2e per kWh. Therefore the calculation is (7):

$$\textbf{Emissions}_{\textbf{milling}}\textbf{=50×0.4=20 kg CO}_2\textbf{e per ton of wheat} \quad (7)$$

Since 1 ton of wheat produces 750 kg of flour, the emissions per kg of flour are calculated as (8):

$$\textbf{20 ÷ 750=0.027 kg CO}_2\textbf{e per kg of flour} \quad (8)$$

The energy efficiency of milling operations depends on the type of milling technology used, equipment maintenance, and energy source. Switching to renewable energy sources could further decrease the footprint.

Emissions from bread production

The baking process involves electricity consumption and additional ingredient inputs. Emission sources include:

- Electricity use: 0.8 kWh per kg of bread, with an electricity emission factor of 0.4 kg CO_2e/kWh and are calculated as (9):

$$\mathbf{Emissions_{baking\ energy}=0.8\times0.4=0.32\ kg\ CO_2e} \quad (9)$$

Bread production is an energy-intensive process, and the choice of baking techniques, oven efficiency, and batch sizes directly influences the carbon footprint. The final total emissions for producing 1 kg of bread are calculated as (10):

$$\mathbf{0.32+0.09+0.0135=0.4235\ kg\ CO_2e\ per\ kg\ of\ bread} \quad (10)$$

This represents the total emissions of converting wheat into a final consumer product. Future improvements in energy efficiency, ingredient sourcing, and production methods can further lower these emissions.

ISO 14064 and ISO 14067

The ISO 14064 standard, developed by the International Organization for Standardization (ISO), establishes principles and requirements for quantifying, monitoring, and reporting greenhouse gas emissions at the organizational level **[4]**. It provides a framework for developing GHG inventories, setting emission reduction targets, and ensuring third-party verification.
In contrast, ISO 14067 focuses on products' carbon footprints (CFP) and outlines requirements for assessing emissions throughout a product's life cycle, from raw material extraction to disposal. This standard aligns with Life Cycle Assessment (LCA) principles and helps companies quantify and communicate their product-related emissions effectively **[5]**.

Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a scientific approach for evaluating the environmental impact of products, processes, or services throughout their life cycle **[6]**. It follows a cradle-to-grave methodology, considering all stages from raw material extraction, production, distribution, use, and disposal. LCA is widely used for carbon footprint assessments, providing a holistic view of emissions and enabling informed decision-making regarding sustainability and emissions reductions **[7]**. LCA is standardized under ISO 14040 and ISO 14044, ensuring reliable, repeatable, and comparable results for environmental impact assessment **[5]**.

Beyond the commonly used methodologies, additional frameworks are gaining attention in carbon footprint assessments:

- Carbon Border Adjustment Mechanism (CBAM): Introduced by the European Union, CBAM places a carbon price on imported goods based on their embedded emissions, aiming to prevent carbon leakage.
- Environmentally Extended Input-Output Analysis (EEIO): This macroeconomic approach estimates carbon emissions at a national or industrial sector level, and it is particularly useful for large-scale policy assessments.
- Dynamic Life Cycle Assessment (dLCA): Unlike traditional LCA, dLCA incorporates time-dependent changes in emission factors and technology advancements, improving long-term forecasting accuracy.

PAS 2050 – UK standard for product carbon footprint calculation

PAS 2050 (Publicly Available Specification 2050) was developed by the British Standards Institution (BSI) to provide a standardized methodology for calculating the carbon footprint of goods and services. PAS 2050 applies a life cycle approach similar to LCA but emphasizes product-specific carbon footprint calculations, particularly for food, energy, and manufacturing supply chains **[20]**. It has been widely adopted as a practical tool for businesses to assess their emissions and develop mitigation strategies.

The GHG Protocol – Corporate Standard is the most suitable for supply chains, as it provides a comprehensive framework for measuring and managing emissions across an organization's entire value chain, including upstream and downstream activities. In contrast, the GHG Protocol – Product Standard, ISO 14067, and PAS 2050 focus on individual product-level carbon footprints, making them more applicable for specific product assessments rather than entire supply chains. Therefore, the GHG Protocol – Corporate Standard and ISO 14064 offer the most effective system-wide approach for assessing and reducing emissions across supply chain operations.

Environmental product declarations (EPD) and their use in the agri-food sector

Environmental Product Declarations (EPDs) are standardized environmental reports that provide transparent and verified data on products' carbon footprints and other environmental impacts. Based on LCA studies, EPDs help companies and consumers make informed choices regarding sustainable products **[2]**. Within the food industry, EPDs are used to compare the environmental impact of different food products, encourage eco-friendly production practices, and support sustainability reporting requirements **[1]**.

Digital tools and software for carbon footprint calculation

Cool farm tool

The Cool Farm Tool (CFT) is a farm-level calculator for estimating greenhouse gas (GHG) agricultural emissions based on empirical models from hundreds of peer-reviewed studies. It focuses on farmers, providing results using readily available data without requiring complex inputs. CFT integrates elements of simple emission factor approaches (IPCC Tier 1) and process-based models (IPCC Tier 3) and covers areas such as farm climate conditions, soil management, crop management, fertilizers, energy use, and transportation. Users must clearly define the boundaries of their analysis, as emissions can be allocated to specific crops or products. The calculation considers soil texture, pH, organic matter content, moisture, and drainage conditions. CFT enables the assessment of energy sources and fertilizer application methods, including organic and synthetic variants. It also accounts for the carbon footprint of transportation based on transport methods and vehicle types. The tool helps farmers identify significant emission sources and optimize mitigation strategies. Managing crop residues and using organic fertilizers can significantly impact a farm's carbon footprint. The results can be used to compare farming practices, but the analysis boundaries must be clearly defined **[21]**.

Agribalyse

Agribalyse is a French research program that was conducted between 2010 and 2013 to develop a unified Life Cycle Inventory (LCI) database for agricultural products **[22]**. The project was initiated by ADEME and involved collaboration among 14 research and technical institutes, including INRA, CIRAD, and Agroscope **[23]**. The primary objective was to support environmental labelling and improve agricultural practices by providing consistent and reliable LCI data **[22]**. The database includes information on more than 100 products, covering the period from 2005 to 2009, with exceptions for perennial crops, where the timeframe extends from 2000 to 2010 **[23]**. Agribalyse follows a cradle-to-farm-gate system boundary, making it suitable for environmental impact assessments and eco-design applications. The program emphasized the need for standardized methodological approaches and identified areas for further improvement, including modelling changes in soil carbon stocks and assessing impacts on biodiversity **[22]**.

Carbon Trust

Carbon Trust is a leading organization in carbon footprint quantification and management, supporting businesses and institutions in implementing decarbonization strategies. Its experts contributed to developing ISO 14067 and the GHG Protocol Product Standard and co-authored the PAS 2050 methodology for product carbon footprint assessment. Carbon Trust developed the *Footprint Expert* software, which is widely used by companies worldwide for carbon footprint analysis. The organization has verified over 37,000 product carbon footprints and provides independent certifications through its carbon footprint labelling system. As a co-author of the *Scope 3 Calculation Guidance* for the WRI/WBCSD Corporate Value Chain Standard, it helps businesses accurately assess emissions across their value chains. Carbon Trust also assists companies in setting Science-Based Targets (SBTi) and developing strategic roadmaps to achieve Net Zero. Additionally, it actively shapes carbon policy and enhances carbon data transparency through independent audits and certification programs **[24]**.

International methodological frameworks for greenhouse gas emission calculation in agriculture: IPCC Guidelines

The 2006 IPCC Guidelines for National Greenhouse Gas Inventories provide comprehensive methodologies for estimating greenhouse gas emissions and removals in the Agriculture, Forestry, and Other Land Use (AFOLU) sector. Volume 4 of these guidelines addresses various land-use categories, including Forest Land, Cropland, Grassland, Wetlands, Settlements, and Other Land, offering detailed methods for each. The guidelines emphasize a tiered data collection and analysis approach, allowing for flexibility based on national capacities and data availability. They also highlight the importance of consistent land representation to track land-use changes accurately. Additionally, the guidelines provide methodologies for estimating emissions from livestock and manure management, N_2O emissions from managed soils, and CO_2 emissions from lime and urea application. Countries can develop transparent and comparable greenhouse gas inventories by following these standardized methods, facilitating effective climate change mitigation strategies **[25].**

Quantification of the carbon footprint in the agri-food sector: key challenges

The quantification of the carbon footprint in the agri-food sector is a complex task influenced by multiple factors that affect the accuracy and reliability of the results. Some of the most significant challenges include:

Data availability and reliability

The lack of accurate and up-to-date agricultural emission data complicates precise carbon footprint quantification. Variations in farming practices and regional conditions often cause this issue. According to **[26]**, collecting reliable emission data from various agricultural activities is challenging, leading to uncertainties in carbon footprint estimates. Standardized and validated data sources remain limited, making cross-sector comparisons difficult. One of the major barriers to carbon footprint quantification is the limited availability of high-quality emission data, especially for smallholder farmers and food producers. For example, while large dairy corporations use standardized methodologies to measure methane emissions from cattle, small dairy farms often rely on national averages, leading to significant discrepancies. The absence of unified databases further complicates cross-sector comparisons. Additionally, the regional variability in emission factors presents another challenge. For example, the carbon footprint of wheat production in Northern Europe differs significantly from that in arid regions due to variations in irrigation practices, soil types, and fertilizer use. This emphasizes the necessity for location-specific emission factors in carbon footprint models.

Complexity of supply chains

Tracking emissions across the entire supply chain is challenging due to its complexity and globalization. Identifying and quantifying emissions from different production, processing, and distribution stages requires detailed data and collaboration between various stakeholders. The complexity of supply chains in the agri-food sector makes it difficult to ensure consistent carbon accounting. Indirect emissions from inputs such as fertilizers, transport logistics, and energy consumption further complicate the process **[27]**.

Standardization of methodologies

Different countries and sectors apply various methodological approaches to carbon footprint quantification, leading to inconsistencies in results. Harmonizing methodologies is essential to ensure comparability and reliability across studies **[28]**. The development of globally recognized frameworks such as ISO 14067 and GHG Protocol has improved standardization, but significant disparities exist, particularly in emission factors, boundary setting, and allocation principles.

Implementation costs for small and medium enterprises (SMEs)

Small and medium-sized enterprises (SMEs) often struggle to adopt carbon footprint monitoring systems due to high implementation costs and limited expertise. Investment in data collection, software tools, and certification can be prohibitively expensive for SMEs. The lack of financial incentives and technical support further restricts their ability to participate in voluntary carbon reporting initiatives. The economic burden associated with carbon footprint accounting varies depending on the methodology used and the complexity of supply chains. For example, conducting a third-party verified ISO 14064 audit or implementing blockchain-based carbon tracking systems can require significant initial investments. These costs pose a substantial barrier for SMEs, as they often lack the financial resources and technical expertise to implement comprehensive carbon accounting frameworks. To facilitate broader adoption, policy support in subsidies, tax incentives, or the development of simplified, low-cost tools is crucial **[26]**.

Lack of integration of carbon criteria into economic models and decision-making

Despite the increasing relevance of carbon accounting, environmental criteria are not sufficiently integrated into economic models and decision-making processes in the agri-food sector. Underestimating environmental costs can lead to decisions not aligned with sustainability goals. A more structured integration of carbon footprint data into cost-benefit analyses, policy frameworks, and investment strategies is necessary to encourage a transition towards low-carbon food systems **[27]**.

Trends and perspectives in carbon footprint monitoring

Monitoring carbon footprints has become a crucial tool in addressing climate change. Recent trends and perspectives in this field include:

Development of technologies for emission monitoring

The integration of advanced technologies such as Artificial Intelligence (AI), blockchain, and IoT sensors is revolutionizing emission monitoring in agriculture. AI enables the analysis of large datasets to predict emissions, while blockchain ensures transparency and immutability in emission records. IoT sensors provide real-time data on farm conditions, allowing for more accurate tracking and management of emissions. The importance of digital technologies in agriculture for improving environmental management is emphasized **[29]**.

Linking carbon footprint to ESG assessment

Integrating carbon footprint metrics into Environmental, Social, and Governance (ESG) assessments is becoming a standard in corporate sustainability evaluations. Investors and regulators increasingly demand transparency in greenhouse gas (GHG) emissions, influencing companies' access to financing and market reputation. ESG reporting is a critical tool for investors to assess environmental risks **[30]**.

Future EU legislative requirements for the carbon footprint of food products

The European Union (EU) is moving toward stricter legislative requirements for carbon footprint reporting in the food industry. The objective is to reduce GHG emissions across the entire food supply chain and promote sustainable agricultural practices. The Regulation (EU) 2024/1781, adopted on May 13, 2024, emphasizes the need to reduce carbon and material footprints and integrate circularity into economic systems **[31]**.

Simplification of methodologies for small and medium enterprises (SMEs)

Due to limited resources, small and medium enterprises (SMEs) often face challenges implementing complex carbon footprint calculation methodologies. There is a growing effort to develop simplified and cost-effective tools that allow SMEs to monitor and reduce their emissions effectively. Johnson and

Schaltegger (2016) propose approaches to streamline environmental management for SMEs, emphasizing the need for adaptable methodologies **[32]**.

Integration of carbon footprint into pricing and consumer decision-making

Consumers' increasing awareness of the environmental impact of their purchasing decisions is driving the integration of carbon footprint considerations into product pricing. Consumers are willing to pay a premium for products with a lower carbon footprint, encouraging companies to adopt emission reduction strategies. Sustainability labeling significantly influences consumer preferences and purchasing behavior. These trends indicate a shift toward a more sustainable economy, where monitoring and reducing carbon footprints are crucial in corporate strategies and consumer choices **[33]**.

Key takeaways and future directions

Quantifying the carbon footprint in the food industry is a complex endeavor that faces several significant challenges. A comprehensive understanding of these challenges is essential for developing effective strategies to mitigate greenhouse gas (GHG) emissions within the sector **[34]**.

The current state of carbon footprint quantification in the food industry

Accurately measuring the carbon footprint of food products involves analyzing emissions across the entire supply chain, from production and processing to distribution and consumption. However, the industry currently lacks standardized methodologies, leading to inconsistencies in data collection and reporting **[34]**. This absence of uniformity hampers the ability to compare and reduce emissions effectively.

Major challenges and potential solutions

1. Data availability and reliability.
   One of the primary obstacles is the scarcity of precise and comprehensive data on emissions at various stages of the food supply chain. To address this, developing open-access databases and implementing advanced monitoring technologies are crucial to enhancing data accuracy and accessibility **[35]**.
2. Complexity of supply chains.
   The intricate and often global nature of food supply chains makes it challenging to trace and account for emissions from all involved processes. Implementing transparent tracking systems and fostering collaboration among stakeholders can facilitate more effective monitoring and management of emissions throughout the supply chain **[36]**.
3. Standardization of methodologies.
   The lack of standardized carbon footprint assessment methods leads to reporting variability and impedes comparability. Establishing unified protocols and guidelines is essential to ensure consistency and reliability in emission measurements **[34]**. Regulatory bodies such as the International Organization for Standardization (ISO) and the Greenhouse Gas Protocol are pivotal in advancing these efforts.
4. Implementation costs for small and medium enterprises (SMEs).
   SMEs often face financial and technical barriers to adopting comprehensive carbon accounting practices. Developing simplified and cost-effective methodologies tailored to SMEs' capabilities can promote broader participation in emission reduction initiatives **[32]**.
5. Integration of carbon criteria into economic models and decision-making processes.
   Incorporating carbon footprint considerations into economic evaluations and business strategies is vital for driving sustainable practices. This integration ensures that environmental impacts are factored into decision-making, leading to more responsible and informed choices within the industry **[33]**.

Importance of open databases and transparency in emission reporting

Establishing open-access databases is pivotal in enhancing transparency and accountability in emission reporting. Such platforms enable stakeholders to access reliable data, facilitate benchmarking, and promote collaborative efforts toward emission reductions **[37]**. Initiatives like the Emissions Database for Global Atmospheric Research (EDGAR) exemplify efforts to provide comprehensive and accessible emission data for the food sector. In conclusion, addressing these challenges requires a concerted effort to develop standardized methodologies, improve data transparency, and integrate carbon considerations into all facets of the food industry. By overcoming these obstacles, the sector can make significant strides toward sustainability and effectively reduce its carbon footprint **[34]**.

Digital technologies and innovative approaches for reducing the carbon footprint in the agri-food sector

Intelligent emissions monitoring in the supply chain

Digital technologies, such as blockchain, the Internet of Things (IoT), and artificial intelligence (AI), enable more precise and transparent monitoring of carbon emissions in the food sector. Blockchain can ensure data integrity and provide accurate information on a product's carbon footprint from farm to consumer **[38]**. IoT sensors can directly record energy consumption, water use, and emission levels at farms or processing facilities **[29]**. These technologies significantly improve tracking and reporting of environmental impacts across the supply chain **[39]**.

AI applications in optimizing production processes

Machine learning can analyze patterns in agricultural production data, identify inefficient processes, and recommend measures to reduce CO_2, CH_4, and N_2O emissions **[40]**. For example, AI can optimize:

- Fertilizer application: Predictive models can recommend precise fertilizer dosages to minimize nitrous oxide (N_2O) emissions, one of the most potent greenhouse gases in agriculture.
- Irrigation and water management: Sensor–based AI solutions can optimize irrigation schemes to reduce energy consumption and prevent water wastage **[41]**.

Automation and robotics in the food industry

Deploying automated production lines and robotic systems in the food industry can reduce energy consumption and raw material waste **[42]**. Robotics also contribute to precise pesticide and fertilizer application, minimizing environmental impact **[43]**. Automated systems can lower CO_2 emissions by optimizing energy and material usage in food production and distribution **[44]**.

Digitalization of carbon footprint and consumer decision-making

Consumers increasingly demand transparent information about products' environmental impact. Carbon footprint labels or digital applications allow consumers to choose products based on their ecological footprint **[45]**. Eco-labels and certifications, such as Environmental Product Declarations (EPD), can support consumer decision-making in favor of sustainable food choices **[46]**. Studies indicate that consumers are willing to pay more for lower-carbon products if the information is communicated **[47]**.

Critical analysis

The quantification and tracking of the carbon footprint in the agri-food industry represent crucial steps in mitigating environmental impacts and transitioning toward sustainable food production. The sector accounts for approximately 30% of global energy consumption and a significant share of CO_2, CH_4, and N_2O emissions, so the need for standardized methodologies and practical implementation strategies is more pressing than ever. Despite the availability of well-established frameworks such as the GHG Protocol – product standard, ISO 14064, and Life cycle assessment (LCA), several critical challenges hinder the accurate evaluation and management of emissions across the supply chain.

One of the primary concerns is the complexity and variability of emission sources within agri-food systems. Agricultural production involves diverse practices, inputs, and climatic conditions, contributing to inconsistencies in emission factors and data reliability. While robust in structure, current methodologies often struggle to account for these variations, leading to discrepancies in carbon footprint assessments. For instance, calculating emissions from fertilizer use depends on multiple factors, including soil conditions, application methods, and regional climate. Similarly, energy consumption in food processing and distribution varies significantly depending on the technology used and the efficiency of transportation networks. This highlights the urgent need for harmonized protocols that ensure comparability and reliability in carbon footprint quantification.

Another major challenge is the availability and quality of data used in carbon inventories. Many small and medium-sized enterprises (SMEs) within the agri-food sector lack the financial and technical resources to conduct comprehensive assessments, resulting in data gaps and estimation errors. Additionally, integrating carbon footprint tracking into corporate sustainability strategies remains limited due to economic constraints and fragmented regulatory frameworks. While large corporations increasingly adopt carbon accounting practices to meet sustainability targets, smaller entities often struggle to comply with reporting requirements. The development of cost-effective and simplified tools for emission monitoring could significantly enhance participation across all industry levels and improve the overall transparency of carbon data.

The lack of standardized monitoring and reporting protocols further complicates efforts to track emissions effectively. Uniform data collection, processing, and reporting guidelines are essential to enable meaningful comparisons between studies and facilitate meta-analyses that provide insights into global emission trends. Implementing standardized units, consistent system boundaries and harmonized allocation methods would improve the credibility of carbon footprint data. Additionally, integrating digital solutions such as blockchain technology, artificial intelligence, and IoT-based monitoring systems could enhance the accuracy and efficiency of emission tracking, reducing human error and streamlining data management **[48]**, **[49]**, and **[50]**.

Policy and regulatory frameworks are crucial in promoting carbon footprint quantification and reduction within the agri-food sector. While initiatives such as the European Green Deal and stricter carbon reporting regulations have encouraged businesses to adopt emission reduction strategies, there remains a need for comprehensive policies that address the entire value chain. Effective legislation should incentivize sustainable agricultural practices, encourage investment in low-carbon technologies, and support innovative emission reduction solutions research. Furthermore, policy mechanisms such as carbon pricing and emissions trading schemes could drive greater accountability and encourage industry-wide commitments to sustainability.

Public awareness and consumer engagement are also key to successful carbon footprint management. As consumers become increasingly conscious of their food choices' environmental impact, businesses can align their strategies with market demand for sustainable products. Transparent labeling systems that provide clear information on the carbon footprint of food products can empower consumers to make informed purchasing decisions. Additionally, educational campaigns on the benefits of reducing food waste, choosing locally sourced products, and supporting sustainable farming practices can collectively contribute to emission reduction efforts.

Scientific advancements and interdisciplinary collaboration will be fundamental in overcoming current limitations in carbon footprint quantification. Research efforts should focus on refining existing methodologies, improving emission factor databases, and developing innovative mitigation strategies. Collaboration between food scientists, environmental researchers, policymakers, and industry stakeholders is essential to translate scientific findings into practical applications that drive meaningful change. The development of open-access databases and knowledge-sharing platforms can further facilitate the exchange of best practices and foster a collective approach to tackling emissions in the agri-food sector.

In conclusion, quantifying and tracking carbon footprints in the agri-food industry are vital for achieving climate goals and transitioning towards a more sustainable food system. Addressing the challenges related to data accuracy, standardization, and economic feasibility requires coordinated efforts across scientific, regulatory, and industrial domains. By implementing harmonized methodologies, investing in technological innovations, strengthening policy frameworks, and promoting consumer engagement, the sector can significantly reduce its environmental impact and contribute to global sustainability efforts. The path forward demands a commitment to transparency, collaboration, and continuous improvement in carbon footprint assessment and mitigation strategies.

Another critical aspect of carbon footprint reduction in the agri-food industry is the influence of climate change itself. As global temperatures rise, changes in precipitation patterns and soil conditions will alter emission factors for agricultural production. For example, higher temperatures may accelerate soil organic matter decomposition, increasing CO_2 release. Additionally, new regulatory measures such as the Carbon Border Adjustment Mechanism (CBAM) will introduce financial penalties for high-emission imports, further incentivizing decarbonization.

CONCLUSION

The quantification and reduction of the carbon footprint in the agri-food sector are essential steps toward mitigating climate change and achieving carbon neutrality. Despite the availability of established methodologies such as the GHG Protocol, ISO 14064, and Life Cycle Assessment (LCA), significant challenges persist, particularly in data reliability, methodological standardization, and economic feasibility for small and medium enterprises. Addressing these issues requires harmonized monitoring frameworks, transparent data reporting, and the integration of emerging technologies such as artificial intelligence and blockchain. Policy interventions, including stricter regulatory frameworks and financial incentives, will foster decarbonization efforts across the food supply chain. Consumer awareness and behavioral shifts towards sustainable food choices reinforce the transition to a low-carbon economy. Future research should focus on improving emission factor databases, refining mitigation strategies, and enhancing interdisciplinary collaboration between policymakers, industry leaders, and scientists. A comprehensive and coordinated approach will be critical to ensuring the long-term sustainability of global food systems while minimizing their environmental impact.

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