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Review

The Quantification of Carbon Footprints in the Agri-Food Sector and Future Trends for Carbon Sequestration: A Systematic Literature Review

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Abstract: The growing need for mitigation of GHG emissions generated by the agri-food sector and the production of sufficient, quality food for the growing population, play a prominent role in the planning of global policies and economies. The determination of damaging practices to be reviewed or avoided is achieved by quantifying their Carbon Footprint (CF). With respect to these needs, our research area is the available literature analysing the CF of agri-food products from a life cycle perspective. The reduced availability of studies using this approach results in the lack of a solid basis for the agri-food sector to make a change from in production processes. Quantifying CFs offers the opportunity to act at the most impactful stages of a product's life cycle. In addition to producing products sustainably, it would allow operators in the sector to integrate additional sources of income, through, for instance, participation in the voluntary carbon market or simply by obtaining a premium price for environmental friendly products. The main objective of the study is therefore to understand how the literature deals with the quantification of food CFs, which methodologies it adopts and what insights it provides for future studies that can help policy makers and the sector in question. The review was conducted by applying the PRISMA methodology, which offers guidelines for proper data collection in a literature review. For this purpose, the search was conducted on the Scopus and Web of Science databases. The literature considered highlighted an important historical path in the world of international CF standards with the transition from the ISO/TS 14067 technical specification to the ISO 14067 international standard. However, the range of products analysed is small and no comparative studies on the results obtained by different standards were found. Again, the literature on the subject does not take into account consumer perceptions of low-carbon products nor the economic perspectives of operators. The information we have obtained from our study provides a solid basis for future research, which should focus on increasing the number of agri-food products analysed and examining which parts of the production cycle need improvement. This also opens the door to future research scenarios concerning possible alternative sources of income for those who produce in a carbon-neutral manner and the benefits for consumers willing to buy them.

Keywords: sustainability; LCA; CF; consumer; carbon market

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1. Introduction

The close relationship between world population growth and rising agricultural production is coupled with a directly proportional increase in climate change. The production of greenhouse gases (GHGs), carbon dioxide, methane and nitrous oxide, generated massively by human activities, is responsible for this. These gases are defined as "greenhouse" because they capture heat from the sun, warming the atmosphere [1]. The planet's fever is increasing and human activities are sustaining this fast pace. Agriculture, forestry and other forms of land use are responsible for 21% of anthropogenic CO_2 emissions, in the 2010–2019 period [2]. These are generated to meet the need for adequate quantities of food in order to satisfy the world' s population, which will increase by 2.9 million people by 2050 [3]. The climate change linked to the growth rate of agricultural production requires the adaptation of the agri-food system. Hence, there is the need for a more sustainable system that implements climate change-mitigating actions as well as meeting food needs [4]. Research in the field of climate change has long since established that there are several ways in which food production has a negative impact on climate change. Product production, transport and storage along the food supply chain generate different degrees of associated GHGs [5]. Of the total GHGs, 23–42% are attributable to the food system, of which 18% are generated by the supply chain and 6% by food transport [6,7]. A large amount is generated by livestock farming, manure treatment and the use of agricultural machinery [8]. Overall, it can be said that climate change is nothing more than the result of emissions such as methane (CH4) from livestock farming, nitrous oxide (N20) from the application of synthetic fertilisers and carbon dioxide (CO_2) from the combustion of fossil fuels and deforestation of pastures [9]. These emissions are grouped under the term Carbon Footprint (CF) and follow the rule of thumb that "the bigger the Carbon Footprint the bigger the contribution to climate change" [5]. This definition refers to all GHGs mentioned above and not just carbon dioxide or carbon derivatives.

The repercussions of climate change are essentially of two types: direct, as they affect agro-ecological conditions, and indirect, characterised by their influence on economic growth, which consequently affects the demand for agri-food products. While the agricultural sector is trying to adapt production levels to the rate of world population growth, it is also having to respond to an ever-increasing number of environmentally conscious consumers, who demand low-carbon products. Consumer awareness of climate change is causing a change in purchasing patterns and food choices [10].

At the same time, operators in the agri-food sector have been called upon to adapt their production systems in line with European policies, where the European Commission has focused its efforts on a more sustainable formulation of the Common Agricultural Policy (CAP). Commitments are also reinforced by strategies such as Farm to Fork and Biodiversity 2030, aimed at increasing organic production, reducing the use of synthetic fertilisers and pesticides and increasing the area under environmental protection by 30% [11].

One of the key issues that makes scientific discussions on GHG emissions' assessment particularly interesting is the definition of the appropriate methodology applicable to agri-food products/systems. The focus on climate change and the need for sustainable agri-food systems makes it necessary to assess impacts throughout a product's life cycle. From this perspective, the CF in a life cycle approach offers the possibility to quantify, in terms of CO_2-equivalents, the environmental burdens associated with each stage of the product. It can also describe how human activities can impose different types of impacts on global sustainability [12]. In the CF methodology, the only indicator considered is Global Warming Potential (GWP), and the mass of CO_2 equivalent based on its 100-year global warming potential has been accepted as the unit of measurement [13,14].

Given the lack of organisation of knowledge on this topic, a review of the literature is proposed in order to provide insights for future research. The reviews available on the subject differ from our study. They are mainly focused on the explanation of issues and environmental footprints (analysed from the point of view of CF, water footprint, nitrogen footprint, etc.) in the agri-food sector [15], on a single production sector [16], or still analyse sustainability from the perspective of a circular economy [17]. Our work aims to provide a reference overview of CF studies in this field by analysing the different methodologies and standards that use a life cycle perspective.

The work was guided by two research questions. The first aims to provide a descriptive framework of the existing literature on CFs applied to the agricultural sector, highlighting trends in this field of research. The second one aims to direct future research flows towards a changing socio-economic context. To answer the following Research Questions (RQ), a systematic review of the literature was carried out:

RQ1: How does the scientific literature analyse the CF applied to the agricultural system?

RQ2: What are the scenarios for future research?

This paper is structured as five sections: the Section 2 describes the research methodology used in this study to conduct a systematic literature review. Section 3 presents the results in terms of the main criteria used in the analysis. Sections 4 and 5 discuss the arguments related to these research questions and draw conclusions.

2. Materials and Methods

2.1. Literature Review

In order to provide a comprehensive view of how much and how the CF methodology is suitable for assessing the sustainability level of agricultural production, a systematic review of the existing scientific literature was conducted. According to Grant and Booth [18], this type of review aims to systematically evaluate and synthesize research. It is transparent in reporting its methods, being easily replicable by others. Systematic reviews attempt to compile all known knowledge on a topic; in recent years there has been a noticeable shift towards the inclusion of a wider range of study designs incorporating quantitative, qualitative and mixed studies [18].

The study focused on conducting a review by applying the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method [19], in order to ensure quality assurance during the revision process and make the study replicable. It was also used as a formal systematic review guideline for data collection [20]. The set of keywords selected for the creation of the PRISMA flowchart was selected based on the search questions, which consisted of searching for papers proposing the study of the carbon footprint in the agri-food sector with a life cycle approach, considering the consumer and his perception of low-carbon products.

As Table 1 shows, the databases used for the search are Scopus and Web of Science (WOS), within which the following strings were used. In the Scopus database, a search was performed in the fields "title", "abstract" and "keywords" for the words carbon footprint, life cycle and consumer and in "all" fields for the word agriculture. In the Web of Science database, the search for the words carbon footprint and life cycle was in the "topic" field and agriculture and consumer in "all" fields.

Table 1. Queries used to search the databases.

Database	Search Strings
Scopus	(TITLE-ABS-KEY (carbon AND footprint) AND TITLE-ABS-KEY (life cycle) AND ALL (agriculture) AND ALL (consumer))
Web of Science	TOPIC: (carbon footprint) AND TOPIC (life cycle) AND ALL FIELD: (agriculture) AND ALL FIELD (consumer)

The search on the Scopus and WOS databases led to 237 results, 144 for the former and 93 for the latter. From these, 39 papers were excluded as duplicates. Further screening was then carried out using the 'Refine Results' function of the databases in order to exclude reviews and editorial materials and include only articles written in English. A second screening was carried out based on the abstract content, excluding off-topic studies and those not focused on the agri-food sector or carbon footprints. In this way, 60 articles were assessed for eligibility through in-depth reading of the full text.

Through the selection process described, the total number of papers found was reduced to 27 representative articles that were included in the descriptive analysis. These were read in full and analysed one by one for the purposes of this study. The above is summarised in Figure 1.

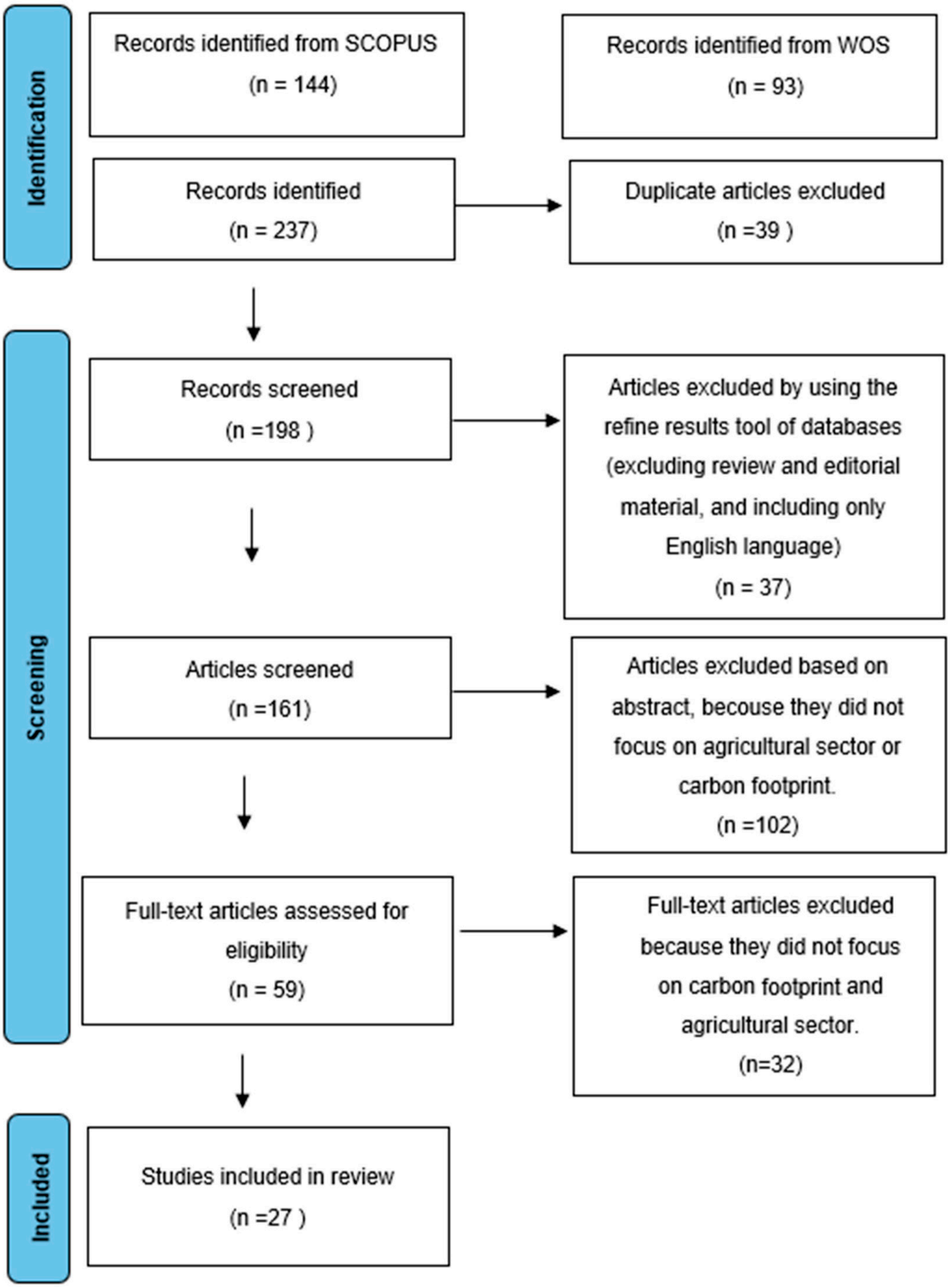

Figure 1. Methodological steps of the literature search process using the PRISMA flow diagram.

2.2. Characterisation of Matrix Criteria for the Descriptive Analysis

In order to summarize the results of the research, an evaluation matrix was constructed, which allowed the papers to be classified according to various criteria. These are shown in Table 2. The selected papers were classified on the basis of the place of research, in relation to the scientific field of application, the product analysed and the method of assessing the carbon footprint.

Table 2. Matrix criteria for the descriptive analysis.

Criteria	Description
Place of the research	Where the case study took place
Field of application	Context in which the application was implemented
Product of reference	What was the product analysed
Carbon footprint assessment methods	Different types of methods used

3. Results

3.1. Descriptive Analysis

The descriptive analysis was carried out based on the distribution of the papers considered in the review, by year and country in which the case study was conducted, by the field of research application, by the main product under study and by the methodology applied in the establishment of the CF in the agricultural sector. To analyse the development of research in the field of CFs and to understand the trends in the scientific fields, the 27 selected articles are presented. As Figure 2 shows, they were published between 2011 and 2022. The results show an exponential growth in the number of papers published on this topic in the year 2015 and between 2018 and 2019. It is only in the last few years that scientific publication on CFs has been almost constant. The first publications date from 2011 to 2013, covering the CFs of butter and blends as well as different types of packaging and product waste at the consumer level [21]; the production and consumption of sliced bread [22]; the export of yellow melons produced in Brazil [23]; and the CF of bananas, following the life cycle along the value chain [24]. Only recently, in the 2015–2022 period, has the scientific community focused more on calculating CF using a life cycle approach. In order to counteract climate change phenomena, it is necessary to provide detailed information on agricultural practices and production that potentially generate a large amount of GHGs [25], increasing the number of products analysed with this methodology.

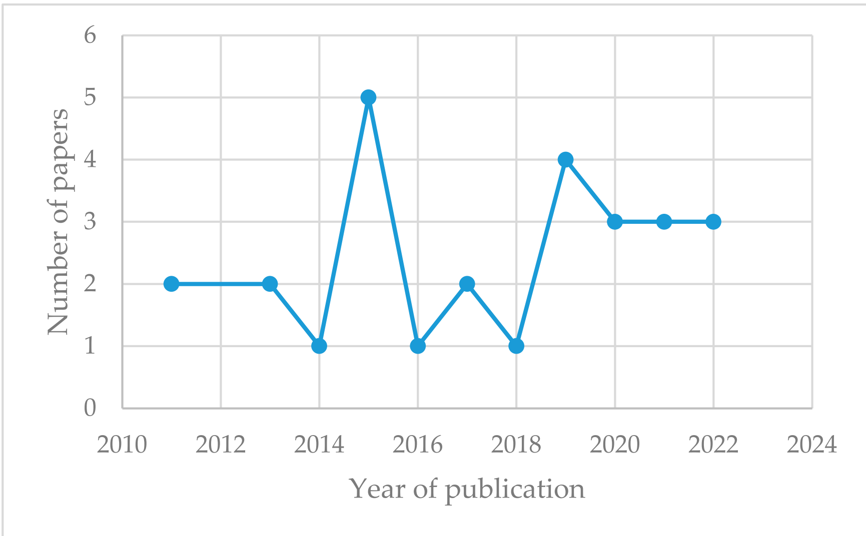

Figure 2. Publication trend per year.

In relation to the place of publication, Figure 3 shows the geographical distribution by country. Of the works considered, 19% were published in Italy, followed by 15% in China. At the same percentage (7% per country) were the UK, Brazil, Japan, Germany, New Zealand and Spain. A lower percentage of publication can be found in countries such as Denmark, Norway, India, Ecuador, the USA and Chile with 4% each of papers on the topic in question. The country with the largest number of publications on CFs in the agricultural sector at the moment is Italy, which can be explained by the great interest shown by consumers in environmental issues and GHG reduction, as well as a greater willingness to pay for low-carbon food products [26].

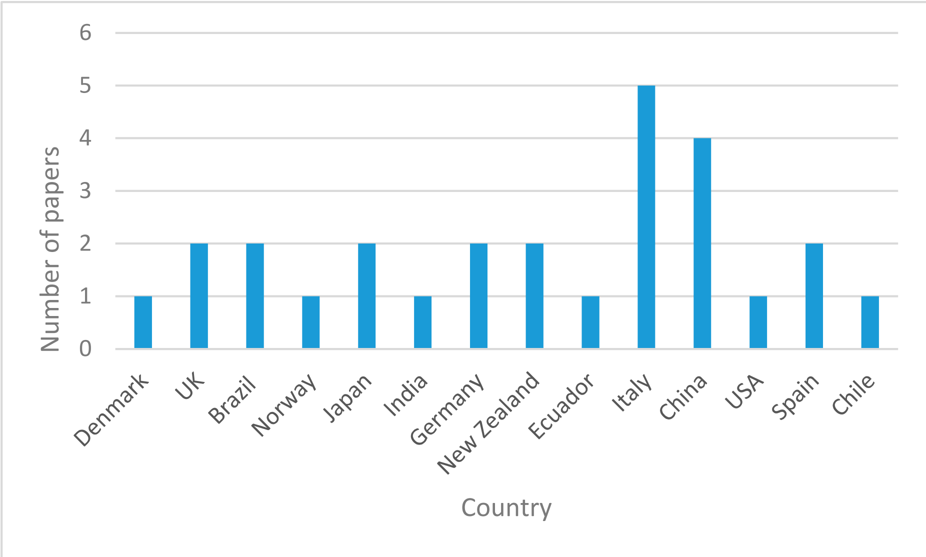

Figure 3. Geographical distribution by country.

Figure 4 shows the results for the field of application of the research considered. The subject of food production, relating to the agricultural phase and the processing or sale of the product, is the one that receives the most attention, with a publication rate of 56%. Of the other articles analysed, 22% focus on the agricultural phase of production, while the remaining 22% is equally divided between research covering the livestock sector and the production of food products made for export to countries other than those of production. The increasing focus on food CFs demonstrates the need for knowledge about the impact of food on climate change [22]. The study of the impact of agricultural processes offers the possibility of combining CFs with the methodologies applied in the study of carbon sequestration in order to better account for production and suggest to farmers the best practices that can be implemented to reduce impact and increase carbon sequestration [27]. In relation to the livestock sector, which is also responsible for GHG emissions, the application of CFs makes it possible to define the best type of livestock farming in order to revitalise the rural environment while maintaining an adequate level of profitability [28]. Another important topic, still little explored in the existing literature, is the production of food for export, compared to numerous studies covering the entire cycle of the product produced and consumed in the same country. The analysis of the entire supply chain makes it possible to identify hot spots and measures to be taken in exporting countries [29].

Figure 5 shows the products considered in the reference literature. It can be seen that a great deal of interest was found in the wine sector [30–32], livestock [28,33,34] and different horticultural products [35,36]. Other work on fruit and vegetables considers crops such as melons [23], bananas [24,37], kiwi [38], tomato [39], spinach [40], apples [29] and blueberry [41]. Several studies have been conducted on milk, one of which deals with the comparison between milk of animal origin and plant-based milk [42,43]. The review also contains work on products such as butter [21], tea [44,45], coffee [46], bread [22], sandwiches [47] and meals for school canteens [48]. One paper deals instead with different products such as wheat, maize, apples and rice [27].

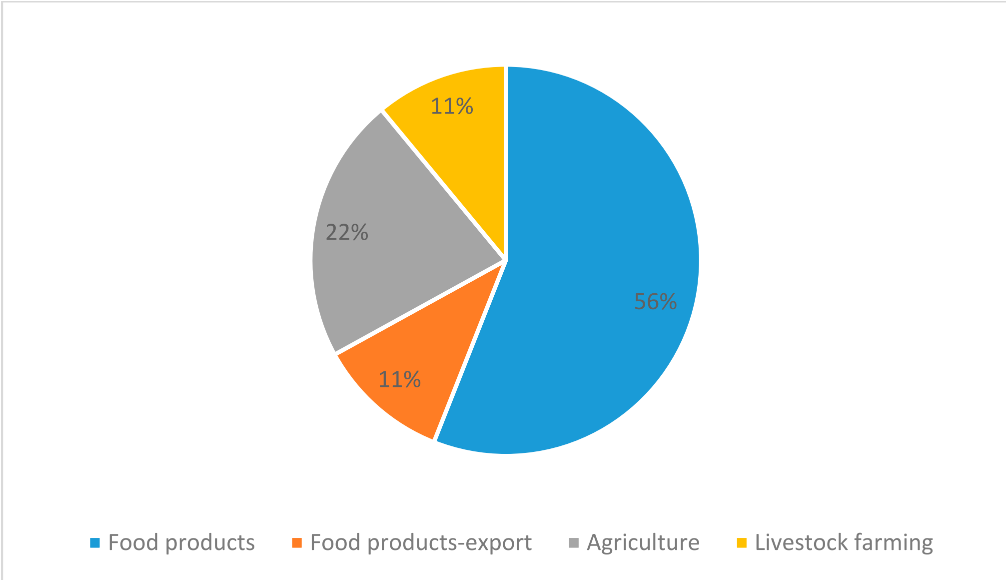

Figure 4. Field of application.

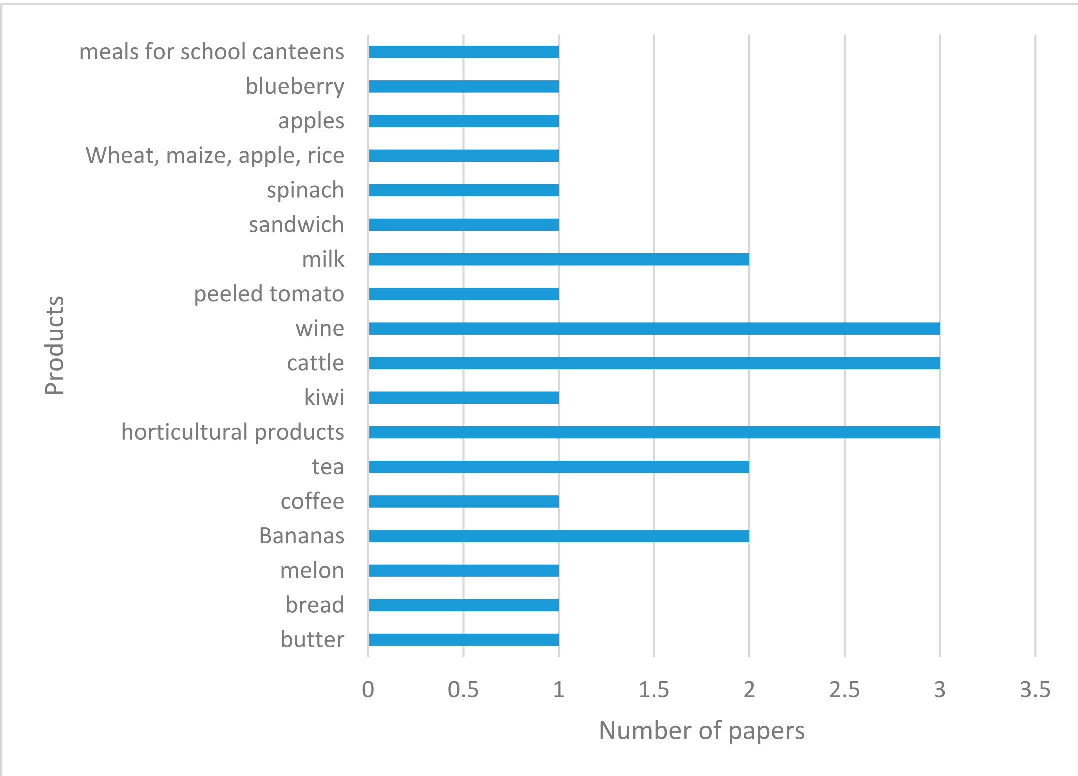

Figure 5. The main reference products.

3.2. *Carbon Footprint Assessment Methods Based on Life Cycle Approaches*

The methodological approach used in the papers under review is a Life Cycle Assessment (LCA), following ISO 14040/44 standards [49,50]. It determines the importance of environmental assessment in the implementation of sustainable development objectives [15]. LCA is widely used in determining the environmental footprint of food products by considering their life cycle [51]. Studies of this type require tracking the product from field to consumption, and also considering all operations that do not directly affect the production process, but are indispensable to the final product. For example, the agricultural phase involves the use of machinery, the production of fertilisers and crop protection products, emissions from the soil and transport [52]. The analysis of the livestock sector, on the other hand, takes into account the production of food, milk, meat, eggs, manure management, slaughter and waste production [15].

Table 3 summarises all the collected papers in which the use of LCA and the related reference standards were found. Flysjo [21] quantifies the CF of butter or blend using the guidelines for animal products provided by the IDF 2010. The characterisation factor used in the study is the IPCC developed with a 100-year perspective, in order to calculate the CF of 1 kg of butter at the customer level and of 1 kg of butter or blend consumed, in Denmark. The author looked at the entire life cycle, considering milk production, milk collection, butter or blend production, packaging, distribution, retail and waste management. Espinoza-Orias et al. [22] are concerned with estimating the carbon footprint and identifying the life cycle hotspots of white and wholemeal bread produced and consumed in the UK in order to provide a framework for product labelling and consumer communication. The methodology used in the study is the LCA, according to the PAS 2050, which is based on specific rules that prefer primary data to secondary data. It is appropriate for business-to-consumer communication and carbon labelling. The authors also apply LCA according to the ISO 14040 (which also uses secondary data) in order to compare the results obtained with the two methodologies. The LCA methodology for determining CF was also applied by Brito de Figueiredo et al. [23] in their case study of the yellow melon. The reference standards ISO 14040 and 14044 are used to cover the upstream processes of melon production and the downstream processes for transporting the product to another country than the one of production.

Table 3. LCA frameworks in the literature review.

Authors	Case Studies	Impact Evaluation Standards
Flysjo, 2011 [21]	butter and blends	ISO 14040
Espinoza-Orias et al., 2011 [22]	bread	ISO 14040; PAS 2050
Brito de Figueiredo et al., 2013 [23]	yellow melon	ISO 14040
Svanes et al., 2013 [24]	bananas	ISO 14040; ISO/TS 14067
Hassard et al., 2014 [46]	coffee	ISO 14040; PAS 2050
Cichorowski et al., 2015 [44]	tea	ISO 14040; ISO/TS 14067; GHG Protocol
Soode et al., 2015 [35]	horticultural products	ISO 14040
Muller et al., 2015 [38]	kiwi	ISO 14040; PAS 2050
Roibas et al., 2015 [37]	bananas	ISO 14040; ISO/TS 14067; PAS 2050
Ruviaro et al., 2015 [33]	livestock farming	ISO 14040
Rinaldi et al., 2016 [30]	wine	ISO 14040; ISO/TS 14067
Garofalo et al., 2016 [39]	tomato	ISO 14040
Reisinger et al., 2016 [42]	milk	ISO 14040
Espinoza-Orias et al., 2018 [47]	sandwich	ISO 14040; PAS 2050
Seo et al., 2019 [40]	spinach	ISO 14040
Hu et al., 2019 [45]	tea	ISO 14040; PAS 2050
Hu et al., 2019 [36]	horticultural products	ISO 14040
Ponstein et al., 2019 [31]	wine	ISO 14040; GHG Protocol
Chen et al., 2020 [27]	wheat, maize, apple, rice	ISO 14040
Tallaksen et al., 2020 [34]	livestock farming	ISO 14040
Escribano et al., 2020 [28]	livestock farming	ISO 14040; PAS 2050
D'Ammaro et al., 2021 [31]	wine	VIVA; ISO 14067
Hu et al., 2021 [52]	horticultural products	ISO 14040
Iriarte et al., 2021 [29]	apples	ISO 14067
Coluccia et al., 2022 [43]	milk	ISO 14040
Perez et al., 2022 [41]	blueberry	ISO 14040; GHG Protocol
Volanti et al., 2022 [48]	meals for school canteens	ISO 14040

Svanes et al. [24] analysed the life cycle of bananas from their production to retail and afterwards into waste, using the methodology provided by ISO 14040 and exploiting the knowledge provided by PAS 2050 and ISO/TS 14067 on horticultural products. The authors stated that the use of the ISO standard was because of its excellent global reputation and because it has become the law in some countries.

Quantification of the CF of different types of coffee products was carried out by Hassard et al. [46] following the global standard PAS 2050 methodology for the application of LCA and using a portion of the respective hot coffee as a functional unit. Cichorowski et al. [44] focused their study on the specifications of ISO/TS 14067 in order to identify the possibilities of GHG reduction throughout the life cycle of tea. Since the ISO does not provide guidance on how to account for the impacts of land use change, the authors also applied the GHG Protocol Product Standard's requirements.

The application of the LCA methodology, based on the GHG calculation method provided by the IPCC with a 100-year perspective, was also used by Soode et al. [35]. Muller et al. (2015) performed a CF calculation using an LCA methodology based on the specifications provided by PAS 2050. Roibas et al. [37] focused their study on bananas using the ISO/TS 14067 standard, following the specifications of PAS 2050, in order to focus on the farming and transport stages, which were the least explored by other authors with respect to their reference crops.

With regard to the livestock sector, Ruviaro et al. [33] applied an LCA methodology, using the method proposed by the IPCC as the GHG calculation approach. The CF of wine was calculated by Rinaldi et al. [30] following the ISO 14067/TS specification, whose principles and guidelines also cover the goods and services. The ISO 14040 was also used by Garofalo et al. [39] to quantify the GHG emissions of tomatoes and by Reisinger et al. [42] for milk. Espinoza-Orias et al. [47] carried out an interesting study on the CF of different types of sandwiches using LCA methodology and applying the guidelines of the PAS 2050 specification.

Seo et al. [40], Hu et al. [36], Hu et al. [45] and Ponstein et al. [31] also used LCA methodology; in particular, the third example followed the specifications of PAS 2050 for the development of an LCA and the last example relied on the GHG protocol specifications to assess direct emissions generated in the vineyard and on the winery premises, indirect emissions from the use of electricity and other indirect emissions generated upstream and downstream of production.

Quantifying the CF of agricultural processes can be accomplished using the LCA methodology, as shown by Chen et al. [27].

Tallaksen et al. [34] and Escribano et al. [28] also applied the LCA methodology for studies in the livestock sector. The latter also follows the specifications of PAS 2050.

D'Ammaro et al. [32] proposed the quantification of a wine CF using an innovative life cycle methodology approach. It involves the application of a VIVA methodology that is based on the ISO 14067 standard, which, as of 2018, has become a standard and not just a technical specification as in previous work.

Hu et al. [52] calculated the CF of different horticultural products produced on different types of farms and an LCA methodology according to ISO 14040 was also used for this purpose.

The research conducted by Iriarte et al. [29], which is more recent than the work considered above, also refers to the ISO 14067 standard for the CF of apples according to a life cycle approach.

Coluccia et al. [43], for the quantification of the CF of milk in comparison with soya milk, used an LCA with the IPCC calculation method over a 100-year time period. Finally, the last two studies considered, produced in 2022 [41,48], also use ISO 14040 with the addition of the GHG Protocol specifications for [41].

4. Discussion

The growing focus of research and policy makers on issues such as sustainable development, climate change and the need to feed the growing population, requires sustainable production and providing food business operators with environmentally acceptable practices for achieving sustainability. For these reasons it is necessary to study the quantification of GHG emissions in depth and exhaustively, for the reader.

In light of the results obtained, it can be stated that LCA and the life cycle approach are the only robust method for quantifying CF in the agri-food sector. The differences found during the analysis of the papers are only based on the technical specifications adopted by the authors. These are to provide principles, requirements and guidelines for CF calculation, based on and applying the ISO 14040 standard [49,50]. In total, 48% of the works considered calculated CF by applying an LCA according to ISO 14040, and without using any technical specification; 22% added the PAS 2050 specification guidelines to this methodology in order to have more detailed references to follow; 7% of the authors used the ISO/TS 14067 technical specification before 2018, when it was replaced by the ISO 14067 standard. Still, it was 7% of the authors who used more than one technical specification for their studies and the same percentage was registered for the works in which the GHG Protocol and ISO 14067 were used, after its release as an International Standard.

The above shows the current trend of research in the field of CFs in the food sector, but what could guide future research is the comparison of the results obtained with the different existing standards (ISO 14040 and 14067) and the increase in the portfolio of food products analysed, in order to make the consumer increasingly aware of his or her food choices.

This study also highlighted the lack of analysis of consumer perceptions of low-carbon products and their willingness to pay for them. People who attach importance to ecological traits appreciate the quality and added value of environmentally friendly production much more. These consumers are also more willing to pay a higher price for products with a lower carbon footprint, as opposed to those who make their choices solely on the basis of price, for whom the environmental impact of the product is not an argument for buying a more expensive but more environmentally friendly product [15]. Future research could be directed at combining the study of CFs with the analysis of consumer behaviour towards these products in order to encourage producers to take the product labelling route. Analysing consumer preferences regarding the purchase of products with a lower CF makes it possible to understand what drives their choices and to define the mitigation potential for the agricultural sector resulting from these purchasing processes [26]. Indeed, as De Pelsmacker et al. [53] noted, when it concerns sustainability, a determining element is the inclination of the "ethical consumer [that] feels responsible towards society and expresses these feelings by means of his purchase behaviour".

Another option for future research could be to combine CF calculation with the definition of practices that sequester carbon by storing it in the soil in order to generate carbon credits for the voluntary market. Voluntary CO_2 markets and eco-labelling schemes can draw inspiration from CO_2 sequestration assessment in order to find an operational starting point for their implementation [54]. The definition of agricultural practices rich in mitigation and the identification of economic incentives to promote their adoption among farmers could be deepened to emphasise the importance of the carbon sequestration and CF quantification of a production process [54,55].

5. Conclusions

Within political spheres around the world, the concept of sustainable development is becoming increasingly important. Achieving the latter, in order to counteract climate change phenomena and to provide sufficient, quality food for the growing population, translates into meeting current and future needs in an environmentally friendly way. The agri-food sector is a major contributor to resource consumption, in terms of energy, water, soil and chemicals, used in agriculture and food packaging. In light of this, understanding what causes CO_2-eq emissions and implementing actions to reduce them are achievable goals through CF quantification. For this purpose, the methodological approach used in the scientific literature is the life cycle approach, in order to assess agricultural production, processing, product delivery to the consumer, production and waste management. The research questions we set out to answer concerned how the literature analyses the CFs of agri-food products and what the scenarios are for future research. With respect to the former, it became apparent that the methodology widely applied by researchers in the field is Life Cycle Assessment according to the ISO 14040 standard, without any technical specification, while only a small portion of the studies applied ISO 14067, which is dedicated to product CF studies. From this emerges the need to broaden the research involving the application of product CF studies by increasing the range of products analysed, which is also small compared to the range of agri-food products available on the market and in different production contexts. With regard to the second research question, on the other hand, the future scenarios to be analysed should be aimed at suggesting improvements to be made in the most impactful phases of the production cycle, as well as carrying out studies on the possible economic opportunities for operators in the sector. The latter should be encouraged to produce more sustainable products both through the possibility of obtaining a premium price and through participation in the voluntary carbon market, which represents a valid system of exchange between emitters and sequesters of GHGs in the atmosphere. To conclude, it is precisely the consumer that could be the determining factor in the popularity of low-carbon and environmentally friendly products, which is why it is hoped that future research will include analysis of consumer perceptions and their purchasing choices.

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