# Carbon footprint of agro-industrial chains: A meta-analysis

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## Abstract

The carbon footprint is one of the most important tools for monitoring greenhouse gas emissions and guiding decarbonization strategies and actions at any scale. This work consists of a literature synthesis based on meta-analysis to understand the logic of the carbon footprint of agri-food products. The literature search was carried out from 2009 to 2023 and after an initial search and review, a total of 154 articles were found. Most of this work was carried out in Europe, accounting for 42%. In terms of agricultural products, milk was the most studied animal product. For crop-based products, vegetable oils and vegetable crops were the main crops subject to carbon footprint calculations. From a methodological point of view, the life cycle assessment is the most widely used approach, especially for products of animal origin. For these products, it was found that the off-farm average (0.69 ± 0.79 Kg $CO_2$ eq/FU) is significantly lower than the on-farm average (3.02 ± 3.18 Kg $CO_2$ eq/FU). On the other hand, correlation analysis could not establish a relationship between production factors and carbon footprint. For plant products, the industrial part generates a more important footprint (65.2 Kg $CO_2$ eq/FU ± 70.9) than the agricultural part (20.0 Kg $CO_2$ eq/FU ± 18.8). In the agricultural part, nitrogen and phosphate fertilization contribute significantly to the carbon footprint (r=0.36 and 0.55 respectively). For the industrial part, electricity contributes to the carbon footprint with a significant correlation of 0.52.

**Keywords:** Carbon footprint, greenhouse gas emissions, decarbonization strategies, agri-food products, meta-analysis

## INTRODUCTION

The world is facing several environmental challenges, including the preservation of natural resources against overexploitation and large-scale pollution, which are the main causes of climate change and its effects (Maja and Ayano, 2021; Maximillian *et al.*, 2019; Rahman, 2023; Singh and Singh, 2017). These challenges have become more acute in the context of population growth, particularly in less developed countries. It involves several activities, including agriculture, forestry, and land use, identifying both sources and sinks of Greenhouse Gases (GHG) (Santos *et al.*, 2022). On the one hand, plants take up carbon dioxide ($CO_2$) and nitrogen (N) from the atmosphere and the soil; these are stored in above- and below-ground biomass, dead components, and soil organic matter during plant growth (Andrén *et al.*, 1990; Devi and Singh, 2023). On the other hand, biological processes involving plant respiration, decomposition and combustion of dead biomass release $CO_2$ and other GHG into the atmosphere, mainly methane and nitrous oxide (Brunori *et al.*, 2017). Anthropogenic land use activities and land use/land cover changes lead to changes in natural fluxes (Hansen *et al.*, 2010; Gütschow *et al.*, 2016; Santos *et al.*, 2022). For instance, food production chains are major contributors to international GHG emissions, and this contribution reaches 25% as reported by Poore and Nemecek (2018) and Mrówczyńska-Kamińska *et al.*, (2021). Food production systems as a group are very heterogeneous, the range of products is large and production systems also vary within product groups (Sonesson *et al.*, 2009). However, there are some common features: firstly, fossil $CO_2$ emissions are less important than those from most other products, with biologically produced GHG emissions being the most important (Sonesson *et al.*, 2009). Secondly, Nitrous oxide ($N_2O$) is often the most significant emission for crop products and monogastric animal production, while methane ($CH_4$) is often the dominant gas emitted from ruminants (Hristov *et al.*, 2013; Xu *et al.*, 2021). Thirdly, the correlation between energy use and climate impact is higher for seafood products, especially for wild fish (Hallström *et al.*, 2019; Sonesson *et al.*, 2009). The climate impact of captured fisheries products is controlled by fossil $CO_2$ emissions from fuel use on fishing vessels (Suuronen *et al.*, 2012). There are numerous exceptions, but generally speaking, plant products emit less per kilogram than animal products like meat and dairy (Xu *et al.*, 2021; Xu and Lan, 2016). A significant part of the life cycle impact of food is caused by consumers (Gruber *et al.*, 2016; Nemecek *et al.*, 2016). In developed countries, car transport from grocery shops is very inefficient, and, overall, cooking can play an important role (Sonesson *et al.*, 2009). Food waste that ends up in landfills also contributes significantly to GHG emissions. Methane is formed when food degrades under anaerobic conditions in landfills (Behera *et al.*, 2010; Sharma *et al.*, 2023). Packaging can be important, but there is a trade-off between the functionality of the packaging, which protects the food, and the emissions from the packaging material (Granato *et al.*, 2022; Lewis *et al.*, 2024). Food production requires land, and fertile land is a scarce resource (Fitton *et al.*, 2019). Therefore, high land use per unit of food produced, i.e., low yield, is negative even if the direct emissions of the product are low (Sonesson *et al.*, 2009). If yield was higher, the


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land could have been used for other production, such as biofuels or forestry. It should also be noticed that the way the land is used, has a significant impact on other environmental issues, like eutrophication and biodiversity loss (Sonesson *et al.*, 2009). Land use is also crucial for valuable ecosystem services, namely the provision of clean water and clean air (Hardelin and Lankoski, 2018). The way the land is managed is also important for the GHG balance of food products (Smith and Gregory, 2013; Sonesson *et al.*, 2009).

The carbon footprint is a measure of the total exclusive amount of carbon dioxide emissions that are directly and indirectly caused by an activity or that is accumulated over the life stages of a product. This includes the activities of individuals, populations, governments, companies, organizations, processes, industrial sectors, etc. Products include goods and services. Across the board, all direct (on-site, internal) and indirect (off-site, external, embodied, upstream, downstream) emissions should be considered (Khaddour *et al.*, 2023; Liu *et al.*, 2022). Only $CO_2$ will be included in the analysis, although other components have a greenhouse warming potential. However, many of these are not carbon-based or are more difficult to quantify due to data availability. The definition also prevents from expressing the carbon footprint as an area-based indicator (Pertsova, 2007). The literature illustrates that there are several units of measurement for the carbon footprint (e.g., mass unit/operating unit, area unit/operating unit, etc.), however, it makes sense to use the mass unit because its conversion to area unit would have to be based on a variety of assumptions, and this conversion would increase the uncertainties and errors associated with a particular estimate of the carbon footprint (Čuček *et al.*, 2012).

Meta-analysis is a systematic review plus a statistical analysis combining data from all the publications identified (Carlin, 2000; Delgado-Rodríguez and Sillero-Arenas, 2018). It leads to an original result that reveals trends that could not be seen in each research article. The review of the available literature explains visible phenomena and identifies potential research for further investigation and improvement. It is in this context that our study employed a systematic scoping review to identify the different approaches to determining the carbon footprint of agro-industrial products and the main sources of GHG emissions. The running of this exercise highlights possible research gaps that can be filled to complete the literature on the subject.

## MATERIALS AND METHODS

### Searched databases and selection criteria

The study used most information found on the Internet regarding the carbon footprint. Thus, publication reports and papers, conference proceedings, press releases, seminars, postgraduate research theses, and websites of retailers and manufacturers were used. The study examined published data over the last decade and searched for information in the following information databases: Google Scholar (https://scholar.google.com/), Science Direct (https://www.sciencedirect.com/), ResearchGate (www.researchgate.net), Scopus (www.scopus.com) and FAO (http://www.fao.org/home/en/). These databases have been selected because of their comprehensive and global nature in terms of information archiving. To access relevant information without bias, broad search terms were used such as carbon footprint and agribusiness. The search terms were coupled with the use of the Boolean operators "AND" and "OR" to provide the following combination: "Carbon footprint AND (Agro-industry OR Biomass OR Crops OR Dairy OR Trees) AND (Agriculture OR Industry) AND Calculation". The search queries were typed into the databases to target 100 results for each database. The literature search was conducted from January 2010 to December 2021. Table 1 and 2 summarizes the results of this search and the logic behind the article's choice. Microsoft Excel was used for the statistical analyses.

### Screening

The screening step is to filter the articles listed and keep the most relevant ones. Rayyan platform (http://rayyan.qcri.org) was used in this work. Rayyan was developed specifically to speed up the initial filtering of abstracts and titles using a semi-automated process, but with the clear aim of incorporating a level of usability compatible with the skills of a wide range of potential users (Ouzzani *et al.*, 2016) and no single method fulfills the principal requirements of speed with accuracy. Automation of systematic reviews is driven by a necessity to expedite the availability of current best evidence for policy and clinical decision-making. We developed Rayyan (http://rayyan.qcri.org. Rayyan allows users to upload citations and full-text articles as part of a single review, or the ability to create several review projects, or even collaborate on publicly available projects. Rayyan aims to offer researchers a one-stop dashboard to work through the details of their processes while also allowing their collaborators the ability to see each other's work. Here, we will review Rayyan on seven criteria: customization, relevance, investment, functionality, searching, collaboration, and support (Johnson and Phillips, 2018). This was based mainly on the analysis of the title and abstract of the article, with a focus on the calculation and the determination of the carbon footprint of agro-products, and any article dealing with something different (e.g., methodological synthesis, development of calculation tools, etc.) was discarded. Figures 1 and 2 illustrate the results of using the 'Rayyan' platform and the approach used to search for articles. Table 3 illustrates the articles related to the carbon footprint of agro-industrial chains, and which took part in the statistical analysis.

## RESULTS

### Geographical and temporal distribution

Figure 3 shows the distribution of the selected published papers by continent. Most carbon footprint studies have been conducted in Europe. 64 wrote articles during the analysis period (42%). On the European continent, Spain seems to be a country where carbon footprint studies are becoming increasingly important; 20% of European work is done in Spain. Most of this work concerned dairy

**Table 1: Pertinent articles that focus on the carbon footprint associated with agro-industrial chains and that were included in the statistical analysis. This compilation encompasses research papers, case studies, and reviews that investigate various aspects of carbon emissions in the context of agri-industrial processes**

| Title | Authors | Country | Continent | Topic/subject | Product |
|---|---|---|---|---|---|
| A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms | O'Brien *et al*. (2014) | Ireland | Europe | Livestock production | Milk |
| An Analysis of Carbon Footprint of Vegetable Production in Jiangsu, China | Yan et al. (2012) | China | Asia | Crop production | Vegetable crops |
| Agricultural Carbon Footprint Is Farm Specific: Case Study of Two Organic Farms | Adewale *et al*., (2019) | USA | America | Crop production | Vegetable crops |
| An appraisal of carbon footprint of milk from commercial grass-based dairy farms in Ireland according to a certified life cycle assessment methodology | O'Brien, Brennan, *et al*., (2014) | Ireland | Europe | Livestock production | Milk |
| Calculation of the carbon footprint for family farms using the Farm Accountancy Data Network: A case from Lithuania | Dabkienė *et al*., (2020) | Lithuania | Europe | Crop production | Vegetable crops |
| Carbon footprint along the Ecuadorian banana supply chain: methodological improvements and calculation tool | Roibás *et al*., (2016) | Ecuador | America | Crop production | Banana |
| Carbon footprint of extra virgin olive oil: a comparative and driver analysis of different production processes in Centre Italy | Pattara *et al*., (2016) | Italy | Europe | Crop production | Olive oil |
| Carbon footprint and energetic analysis of tomato production in the organic vs the conventional cropping systems in Southern Italy | Ronga *et al*., (2019) | Italy | Europe | Crop production | Tomato |
| Carbon footprint from dairy farming system: comparison between Holstein and Jersey cattle in Italian circumstances | Della Riva *et al*., (2014) | Italy | Europe | Livestock production | Cattle |
| Carbon footprint of a typical pomelo production region in China based on farm survey data | Chen *et al*., (2020) | China | Asia | Crop production | Pomelo |
| Carbon footprint of a winter wheat-summer maize cropping system under straw and plastic film mulching in the Loess Plateau of China | Luo *et al*., (2021) | China | Asia | Crop production | Wheat |
| Carbon Footprint of agricultural production and processing of tobacco (*Nicotiana tabacum*) in southern Brazil | Boettcher *et al*., (2020) | Brazil | America | Crop production | Tobacco |
| Carbon footprint of an olive tree grove | Proietti *et al*., (2014) | Italy | Europe | Crop production | Olive |
| Carbon footprint of Canadian dairy products: Calculations and issues | Vergé *et al*., (2013) | Canada | America | Livestock production | Dairy products |
| Carbon footprint of cropping systems with grain legumes and cover crops: A case-study in SW France | Plaza-Bonilla *et al*., (2018) | France | Europe | Crop production | Grain crops |
| Carbon footprint of milk from Holstein and Jersey cows fed low or high forage diet with alfalfa silage or corn silage as the main forage source | Uddin *et al*., (2021) | USA | America | Livestock production | Cattle |
| Carbon footprint of milk production in Brazil: a comparative case study | de Léis *et al*., (2015) | Brazil | America | Livestock production | Milk |
| Carbon footprint of crop production in China: an analysis of National Statistics data | Cheng *et al*., (2015) | China | Asia | Crop production | Various crops |
| Crop diversification practice faces a trade off between increasing productivity and reducing carbon footprints | Sun *et al*., (2021) | China | Asia | Crop production | Maize |
| Dairy sheep farms in semi-arid rangelands: A carbon footprint dilemma between intensification and land-based grazing | Escribano *et al*., (2020) | Spain | Europe | Livestock production | Dairy |
| Decreasing the carbon footprint of an intensive rice-based cropping system using conservation agriculture on the Eastern Gangetic Plains | Alam *et al*., (2019) | Bangladesh | Asia | Crop production | Rice |
| Effect of different crop management systems on rainfed durum wheat greenhouse gas emissions and carbon footprint under Mediterranean conditions | Alhajj Ali *et al*., (2017) | Italy | Europe | Crop production | Wheat |

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|---|---|---|---|---|---|
| Greenhouse gas emissions and carbon footprint of cucumber, tomato and lettuce production using two cropping systems | Pereira *et al*., (2021) | Brazil | America | Crop production | Vegetable crops |
| Identifying the main crops and key factors determining the carbon footprint of crop production in China, 2001–2018 | Chen *et al*., (2021) | China | Asia | Crop production | Various crops |
| Influence of nitrogen application on wheat crop performance, soil properties, greenhouse gas emissions and carbon footprint in central Bhutan | Bajgai *et al*., (2019) | Bhutan | Asia | Crop production | Wheat |
| Integration of ecosystem services into the carbon footprint of milk of South German dairy farms | Kiefer *et al*., 2015) | Germany | Europe | Livestock production | Milk |
| Assessment of carbon footprint and energy performance of the extra virgin olive oil chain in Umbria, Italy | Rinaldi *et al*., (2014) | Italy | Europe | Crop production | Olive oil |
| Carbon footprint of dairy goat production systems: A comparison of three contrasting grazing levels in the Sierra de Grazalema Natural Park (Southern Spain) | Gutiérrez-Peña *et al*., (2019) | Spain | Europe | Livestock production | Dairy |
| Lowering carbon footprint of durum wheat by diversifying cropping systems | Gan *et al*., (2011) | Canada | America | Crop production | Wheat |
| Method to assess the carbon footprint at product level in the dairy industry | Flysjö *et al*., (2014) | Denmark | Europe | Livestock production | Dairy |
| Milk Quality and Carbon Footprint Indicators of Dairy Sheep Farms Depend on Grazing Level and Identify the Different Management Systems | Plaza *et al*., (2021) | Spain | Europe | Livestock production | Dairy |
| Potential for improving the carbon footprint of butter and blend products | Flysjö (2011) | Denmark | Europe | Livestock production | Butter |
| Reducing agricultural carbon footprint through diversified crop rotation systems in the North China Plain | Yang *et al*., (2014) | China | Asia | Crop production | Various crops |
| Reducing carbon footprint without compromising grain security through relaxing cropping rotation system in the North China Plain | Zhao *et al*., (2021) | China | Asia | Crop production | Various crops |
| Spatial and temporal patterns of carbon footprints of grain crops in China | Xu, Lan (2017) | China | Asia | Crop production | Grain crops |
| Standard method for determining the carbon footprint of dairy products reduces confusion | Bertrand, Barnett (2011) | France | Europe | Livestock production | dairy |
| The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden | Flysjö *et al*., (2011) | Sweden/New Zealand | Several | Livestock production | Milk |
| Carbon footprint of renewable diesel from palm oil, jatropha oil, and rapeseed oil | Uusitalo *et al*., (2014) | Finland | Europe | Crop production (Bioenergy) | Vegetable oils |
| Water and carbon footprint of selected dairy products: A case study in Catalonia | Vasilaki *et al*., (2016) | Spain | Europe | Livestock production | Dairy |
| Life cycle assessment, C footprint and carbon balance of virgin olive oils production from traditional and intensive olive groves in southern Spain | Fernández-Lobato *et al*., (2021) | Spain | Europe | Crop production | Olive oil |
| Carbon Footprint of Mangosteen Farm Level Evaluation in Eastern Thailand | Pleerux, Aimkuy (2021) | Thailand | Asia | Crop production | Mangosteen |
| Improving the accounting of field emissions in the carbon footprint of agricultural products: a comparison of default IPCC methods with readily available medium-effort modeling approaches | Peter *et al*., (2016) | Germany | Europe | Crop production | Various crops |
| Carbon Footprint and Driving Forces of Saline Agriculture in Coastally Reclaimed Areas of Eastern China: A Survey of Four Staple Crops | J. Li *et al*., (2018) | China | Asia | Crop production | Various crops |
| Environmental assessment of the greenhouse gases emission from poultry production in Russia's central region | Samardzic *et al*., (2018) | Russia | Europe | Livestock production | Poultry |
| Life cycle assessment of olive oil production in France | Belaud, Espi (2012) | France | Europe | Crop production | Olive oil |
| Carbon footprint of China's crop production-An estimation using agro-statistics data over 1993-2007 | Cheng *et al*., (2011) | China | Asia | Crop production | Various crops |
| Can carbon footprint serve as an indicator of the environmental impact of meat production? | Röös *et al*., (2013) | Sweden | Europe | Livestock production | Meat |

| | | | | | |
|---|---|---|---|---|---|
| Methodological complexities of product carbon foot printing: a sensitivity analysis of key variables in a developing country context | Plassmann *et al*., (2010) | Zambia/ Mauritius | Africa | Crop production | Sugar cane |
| Carbon footprint of canned mussels from a business-to-consumer approach. A starting point for mussel processors and policy makers | Iribarren *et al*., (2010) | Spain | Europe | Agri-food | Mussels |
| Carbon and water footprint tradeoffs in fresh tomato production | Page *et al*., (2012) | Australia | Oceania | Crop production | Tomato |
| Carbon footprints of food production in China (1979-2009) | Jianyi *et al*., (2015) | China | Asia | Agri-food | Various products |
| Generic model for calculating carbon footprint of milk using four different LCA modelling approaches | Dalgaard *et al*., (2014) | Denmark | Europe | Livestock production | Milk |
| Life cycle assessment in conventional rice farming system: Estimation of greenhouse gas emissions using cradle-to-gate approach | Abdul Rahman *et al*., (2019) | Malaysia | Asia | Crop production | Rice |
| Uncertainties in the carbon footprint of refined wheat products: A case study on Swedish pasta | Röös *et al*., 2011) | Sweden | Europe | Agri-food | Pasta |
| Carbon footprint and profitability of two apple cultivation training systems: Central axis and Fruiting wall | Vinyes *et al*., (2018) | Spain | Europe | Crop production | Apple |
| The carbon footprint of bread | Espinoza-Orias *et al*., (2011) | United Kingdom | Europe | Agri-food | Bread |
| Environmental assessment of intensive egg production: A Spanish case study | Abín *et al*., (2018) | Spain | Europe | Livestock production | Egg |
| Carbon footprint of grain production in China | Zhang *et al*., (2017) | China | Asia | Crop production | Grain crops |
| Carbon footprint of cotton production in China: Composition, spatiotemporal changes, and driving factors | Huang *et al*., (2022) | China | Asia | Crop production | Cotton |
| Energy use and carbon footprint in response to the transition from *indica rice* to *japonica rice* cropping systems in China | Xi *et al*., (2024) | China | Asia | Crop production | Rice |
| Carbon footprint of farming practices in farmland ecosystems on the North and Northeast China plains | Huo *et al*., (2024) | China | Asia | Crop production | Various crops |
| Carbon footprint of smallholder rain-fed sorghum cropping systems of Kenya: A typology-based approach | Musafiri *et al*., (2023) | Kenya | Africa | Crop production | Sorghum |
| Carbon and water footprints of major crop production in India | Nayak *et al*., (2023) | India | Asia | Crop production | Various crops |
| Carbon footprint of the globe artichoke supply chain in Southern Italy: From agricultural production to industrial processing | Rana *et al*., (2023) | Italy | Europe | Crop production | Artichoke |
| Carbon footprint of hemp and sunflower oil in southern Italy: A case study | Suardi *et al*., (2024) | Italy | Europe | Crop production | Various crops |
| Spatiotemporal Trends of the Carbon Footprint of Sugar Production in China | K. Li *et al*., (2024) | China | Asia | Crop production | Sugar cane |
| The Carbon Footprint of an East African Forestry Enterprise | Parigiani *et al*., (2011) | Tanzania | Africa | Forestry | Forestry products |

**Table 2: Correlation between carbon footprint and animal production factors**

| Production factor | Correlation with Carbon footprint |
|---|---|
| Total feed | -0.02 |
| Electricity | 0.11 |
| On-farm fuel | 0.06 |

**Table 3: Correlation between carbon footprint and Crop-based industries products**

| Production factor | Correlation with Carbon footprint |
|---|---|
| Fungicide | -0.15 |
| Herbicide | -0.3 |
| Insecticide | 0.1 |
| Nitrogen Fertilisation | 0.36* |
| Phosphorus Fertilisation | 0.55* |
| Potassium Fertilisation | 0.07 |
| Electricity consumption | 0.53* |

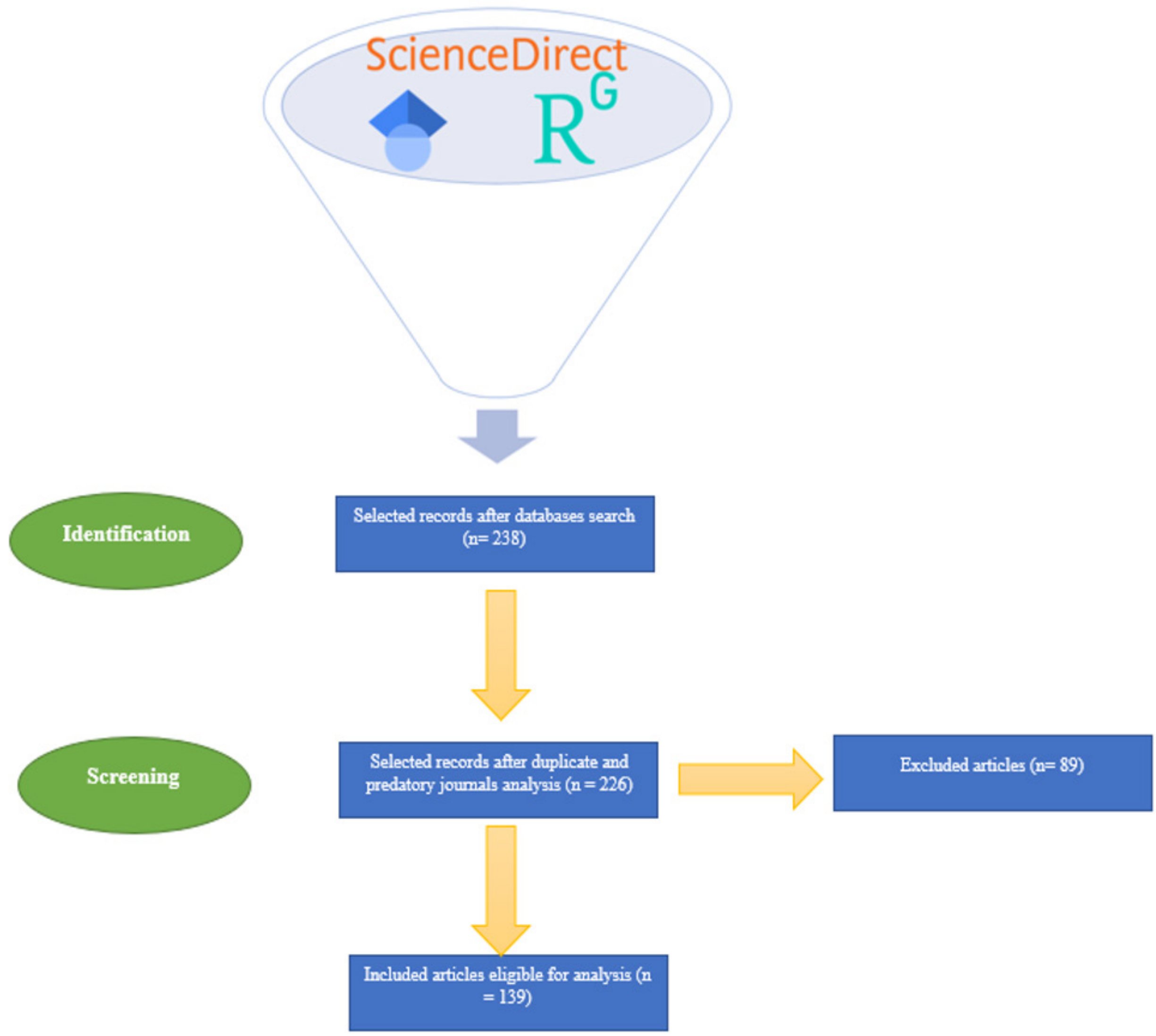


*Figure 2: Flow diagram for selection of eligible papers from databases investigated*

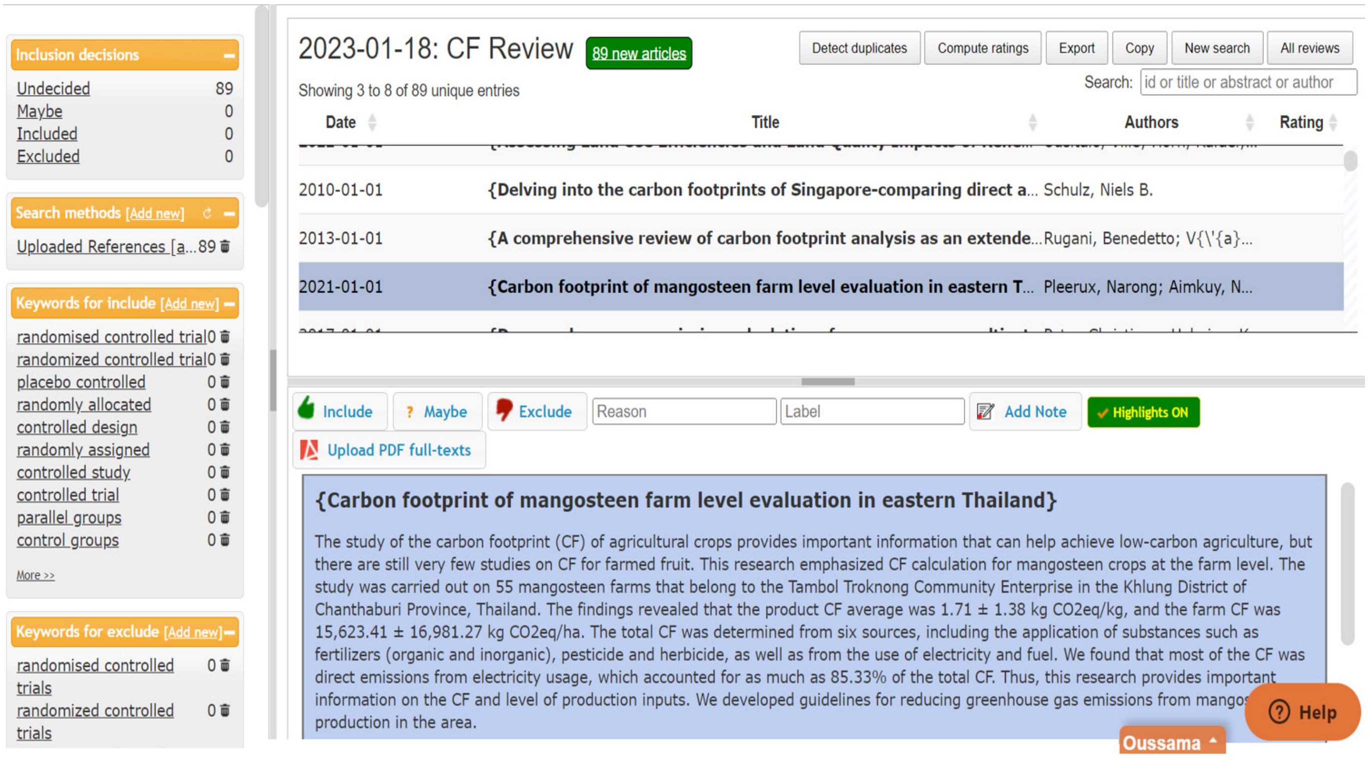


*Figure 1: Screenshot of the results of the screening carried out via the 'RAYYAN' platform*

products. In Italy (13% of European work), the crop sectors are the subject of the carbon footprint calculation, in particular olive oil production and vegetable growing. On the other hand, the calculation of the carbon footprint in the Nordic countries (19% of the work carried out in Europe) mainly targeted dairy products. The Asian continent generates an interesting number of carbon footprint studies for the agro-industrial sector with a share of 32%. The majority of this work was carried out in China (65% of work in Asia), with a strong focus on crop-based industry production chains. America ranks third in scientific output, with a focus on research into meat production in North America and crop-based industries production in South America. However, despite its wealth and agro-industrial diversity, Africa hardly leaves a carbon footprint.

Figure 4 shows the temporal evolution of the production of carbon footprint-related articles in different continents between 2009 and 2023. Over time, interest in this work remains strong. It is noteworthy that the number of works fell slightly in 2020.

## Calculation methodologies

Figure 5 illustrates the breakdown of items according to carbon footprint calculation methodologies. The life cycle assessment (LCA) is the most widely used approach in terms of analysis methodology of the potential environmental impacts of products; with 80 articles proportionate to 61% of the studied works. LCA is a tool for assessing potential environmental impacts throughout a product's life cycle, i.e. H. from the procurement of natural resources through the production and use phase to waste management (including disposal and recycling). The term "product" includes goods, technologies and services. The life cycle assessment is a comprehensive assessment that takes into account the product life cycle and covers a range of environmental impacts (Finnveden and Potting, 2014; Muralikrishna and Manickam, 2017). The methodology proposed by the Intergovernmental Panel on Climate Change (IPCC) is still used to determine the carbon

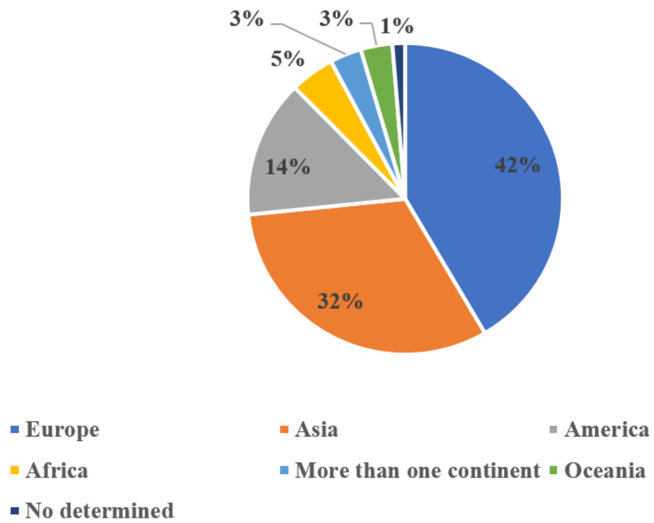


*Figure 3: Geographical distribution of articles studied by continent*

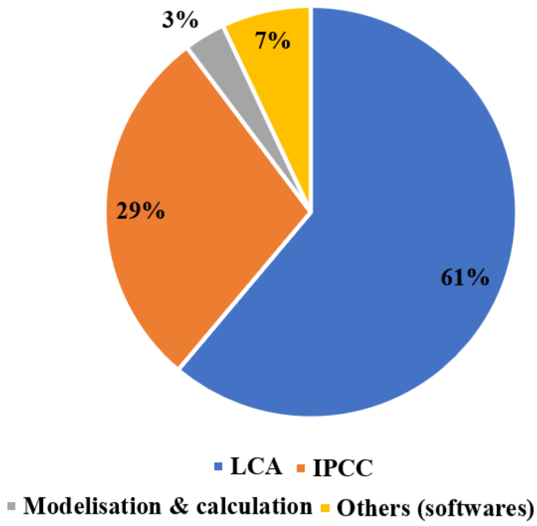


*Figure 5: Breakdown of different carbon footprint calculation methodologies for the articles studied*

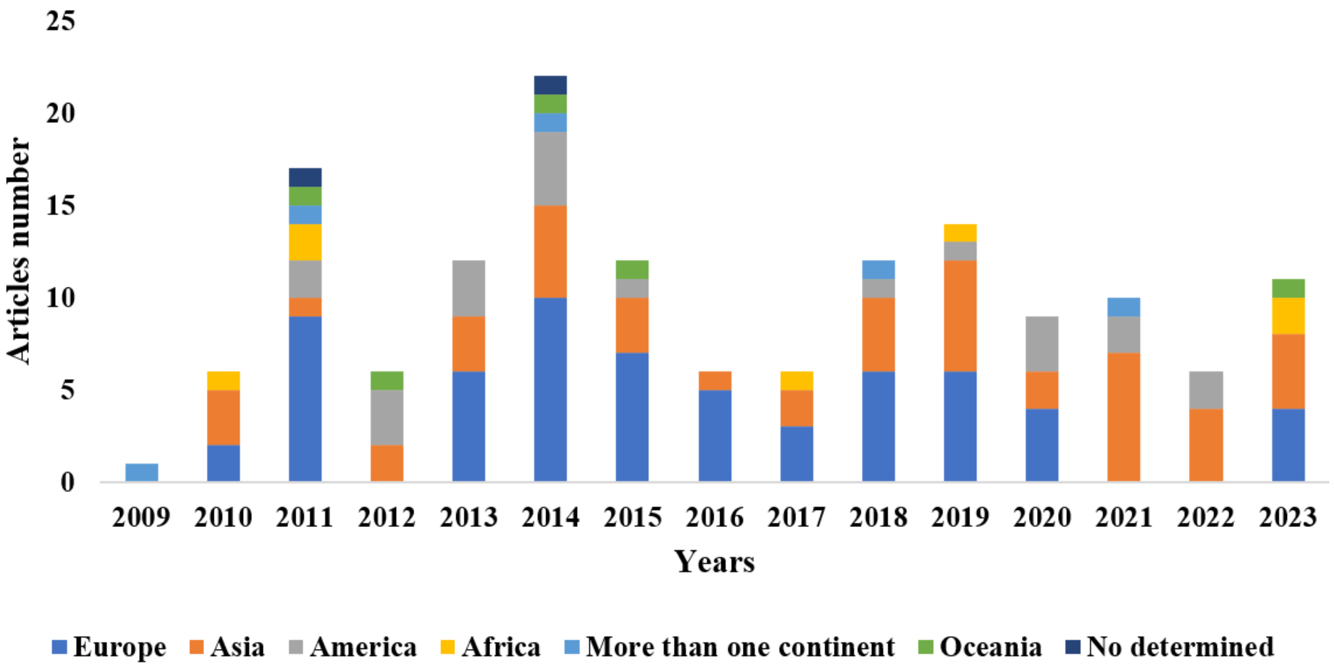


*Figure 4: Space-time distribution of articles studied by continent*

footprint of agro-industrial chains and accounts for 29% of the articles examined. This methodology involves the formulation of emission factors that are used to link the emission of a greenhouse gas for a given source to the amount of activity that causes the emission (IPCC, 2006).

## The carbon footprint of animal products

Animal production is a strongly represented sector in the carbon accounting of agro-industrial sectors; 16% of the articles analyzed are dedicated to the areas of animal production. The carbon footprint of dairy and meat production continues to be a focus (62% and 12% of posts are dedicated respectively to dairy and meat within animal production). From a methodological point of view, life cycle assessment is the most widely used approach (92% of papers are dedicated to animal production).

The definition of the functional unit is the step that initiates each LCA. It provides a basis for comparison between the different ways of achieving the same objectives and is relative to the nature of the case study in question (Dunuwila *et al.*, 2022; Saavedra-Rubio *et al.*, 2022). Regarding milk works, two milk-specific units were frequently investigated, namely "Fat and Protein-corrected milk FPCM" and "Energy Corrected Milk "ECM". 72% of the animal production papers were based on these indicators. ECM is a way to measure the energy content of milk in dairy cows. It is a standardized measure of the energy content of milk in dairy cows that considers the fat, protein, adjusted to 3.5% and 3.2% respectively, as well as the lactose content and weight of the milk produced (Izadi *et al.*, 2021). ECM is used to compare the milk production of different cows (Altech, 2020), and the baseline of current herd performance regardless of their fat and protein content by means of the following formula:

$$ECM = (0.327 \times milk\ weight) + (12.95 \times fat\ weight) + (7.2 \times protein\ weight)$$

FPCM is the estimated quantity of milk calculated on an energy basis of 4.0% fat. This is a way of assessing the milk production records of different dairy animals and breeds on a common energy basis (Berton *et al.*, 2020). For the rest of the articles, except for one article on the carbon footprint of eggs, the unit followed is one kg.

A system boundary is the set of criteria that determines which unit processes, inputs, outputs, and impacts are considered in an LCA. A unit process is a discrete step in the life cycle of a product, e.g. B. Extraction, production, transport, use, or disposal (Suh *et al.*, 2004). The boundaries were divided into two categories: non-agricultural emissions and intra-agricultural emissions. The first category includes emissions related to the production of inputs (e.g. fertilizers, pesticides), the energy used for this production (electricity, diesel, etc.), and the transport of the inputs to the farm. The second category includes emissions from crop-based industries' production of feed in on-site production (combined animal and crop-based industries production), production and transport of milk, as well as all emissions related to processing and final transport.

In our study, the focus was on feed-related factors (amount of feed, number of days grazing, etc.), nitrogen fertilization, and energy components (electricity and diesel). These are the factors for which data is available in all the articles studied. Figure 6 showcases the average carbon footprint values for livestock/animal products. The analysis shows that the off-farm average (0,69 ± 0,79 Kg $CO_2$ eq/functional unit) is lower meaningfully than the on-farm average (3,02 ± 3,18 Kg $CO_2$ eq/functional unit). In the definition of the system, the consideration of on-farm emission components is more important and burdensome than off-farm components; the involvement of crop production (sowing, fertilization, irrigation...) dedicated to livestock feed, for example, as well as the consideration of soil and manure management generates very important emissions which impacts more on the "on-farm" part. Table 4 reveal correlation and regression analysis between animal factor production and the carbon footprint.

## Carbon footprint of crop-based industries products

In contrast to animal products, plant products are characterized by a wide variety. Figure 7 illustrates the distribution of crop species examined in the articles. Vegetable oils (particularly olive and palm oil) and vegetable crops are the main crops subject to the carbon footprint calculation (13%, 8%, and 13%, respectively). The use of area and (or) weight as a functional unit varies from case to case. Often, the use of weight (kg or ton) and the use of the weight-area combination (kg.ha$^{-1}$ or ton.ha$^{-1}$) are the most commonly used approaches (39% each). The contrast to animal production is also reflected in the calculation methodology. Calculations are based on LCA (52% of crop-based industries production articles examined) and

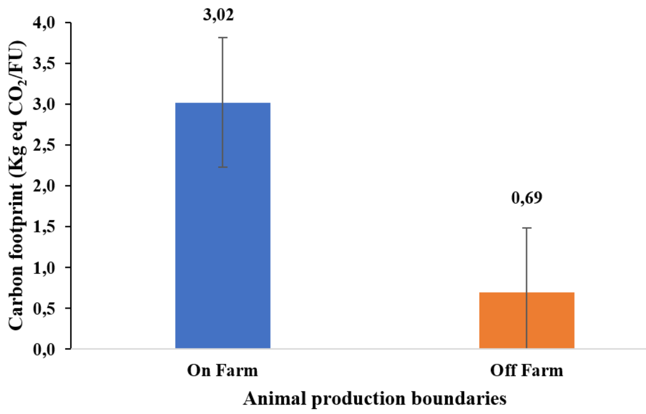


*Figure 6: Average carbon footprint values (kg $CO_2$ eq./FU) for livestock/animal products. For these products, the carbon footprint is subdivided into an on-farm carbon footprint and an off-farm carbon footprint (FU stands for functional unit)*

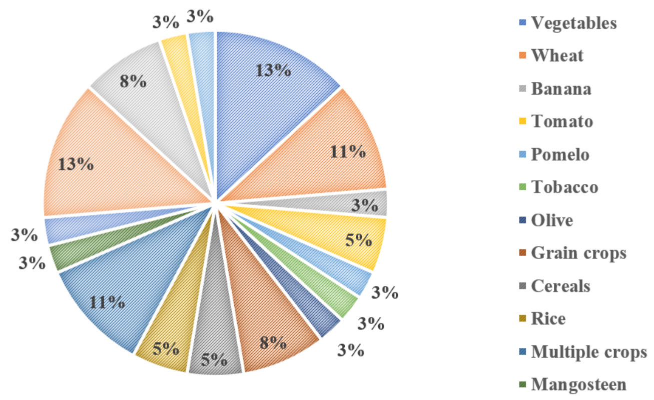


*Figure 7: Breakdown of carbon footprint articles for crop-based industries products according to the crops studied*

IPCC guidelines (37% of crop-based industries production articles examined). Regarding the system boundaries, Figure 8 showcases Major components of the system in the case of crop-based industries. The carbon footprint is composed of an agricultural part, which includes the technical agricultural path from sowing to harvest, and an industrial part, which includes the packaging and industrial processing steps of the agricultural products.

Table 5 summarize the results of the correlation and regression analyses between crop-based industries production factors and carbon footprint. Electricity consumption and fertilization, especially nitrogen and phosphorus, have a significant influence on the development of the carbon footprint, with correlation values of 0.53, 0.36, and 0.55, respectively. Electricity consumption of 1 KWh produces carbon emissions of 2.33 kg $CO_2$/FU equivalent. In terms of fertilization, the consumption of 1 kg of nitrogen contributes to a carbon emission of 3.28 kg eq $CO_2$/FU. Likewise, when 1 kg of phosphorus is consumed, 12.69 kg of $CO_2$/FU are emitted (Figures 9, 10, and 11).

Figure 12 compares the average agricultural and industrial carbon footprint for crop-based industries products. The industrial part produces a more interesting footprint (65.2 kg $CO_2$ eq/FU ± 70.9) than the agricultural part (20.0 kg $CO_2$ eq/FU ± 18.8). Fig. 13 shows the distribution of the agricultural carbon footprint and the industrial carbon footprint in the different cases studied. The average industrial contribution (52%) is slightly higher than the average agricultural contribution (48%).

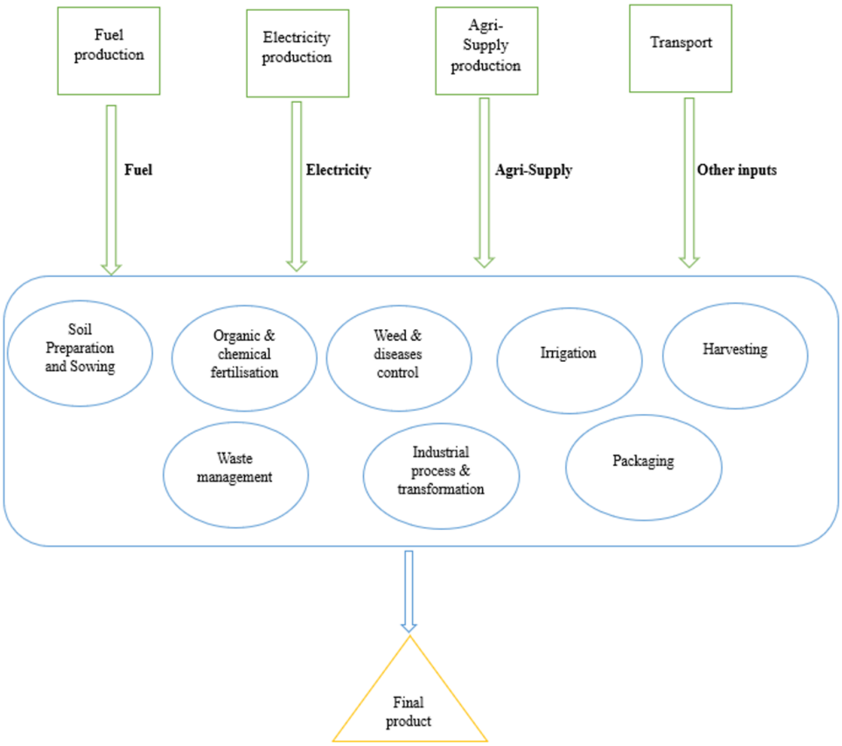


*Figure 8: Main sources of carbon emissions in the case of crop-based industries products*

**Table 4: Tabulated overview of the outcomes of regression analysis, including p-values of 0.1, between carbon footprint and the relevant production factors (case of animal production)**

| Production factor | Regression significance | Regression equation |
|---|---|---|
| Total feed | Not significant | |
| Electricity | Not significant | |
| On-farm fuel | Not significant | |

**Table 5: Tabulated overview of the outcomes of regression analysis, including p-values of 0.1, between carbon footprint and the relevant production factors (case of Crop-based industries products**

| Production factor | Regression significance | Regression equation |
|---|---|---|
| Fungicide | Not significant | |
| Herbicide | Not significant | |
| Insecticide | Not significant | |
| Nitrogen Fertilisation | Significant at 99% level | Y= 3.28 X + 842.48 |
| Phosphorus Fertilisation | Significant at 99% level | Y= 12.69 X + 375.17 |
| Potassium Fertilisation | Not significant | |
| Electricity consumption | Significant at 99% level | Y= 2.33 X + 582.21 |
| Diesel consumption | Not significant | |

## DISCUSSION

Our results show that there is greater interest in carbon footprint studies on some continents than on others. In Europe, for example, there is great interest in calculating the carbon footprint parameter due to its ambitious decarbonization commitments. However, such studies are rare in Africa. Africa's contribution to greenhouse gas emissions is very small. It does not exceed 4% (Al Jazeera, 2023; Kaïré *et al.*, 2015). The African continent is more concerned with developing adaptation to climate change, especially given the drought and pressure on natural resources that Africa is suffering. However, this does not prevent us from highlighting the great potential of the African continent to participate in an interesting climate protection process; The presence of immense reserves of renewable energy sources (solar, wind, biomass) is a key element in positioning Africa at a very important level in the international climate change dynamic. Without forgetting that, this will simply have an important socio-economic impact (job creation, integration of women, involvement in the international carbon market). This mitigation potential to be explored requires the establishment of a culture of calculating the carbon footprint of the various agricultural and industrial value chains.

The industrialized countries' commitment to the Paris Agreement requires them to make radical changes in their production activities. They are more concerned about reducing not only carbon footprint but also other footprints such as energy, water, and others. Life cycle assessment is a very suitable approach for this logic. The distribution of the carbon footprint differs between the animal and plant sectors. On-farm operations emit more carbon than off-farm operations. The focus of mitigation efforts should be on farms. In the case of the plant-based industry, despite the difference between the agricultural and industrial sectors, emissions are very high in both sectors and require mitigation measures.

It is very important to determine the carbon footprint of the agricultural part and the carbon footprint of the industrial part. In the literature, this is not always the case. For example, Proietti *et al.*, (2014) focus on the agricultural part of olive production without tackling the industrial processing of olives. Our analysis showed that, in general, the industrial part is characterized by a higher and more interesting carbon footprint. For crop products, it is believed that Energy consumption, particularly electricity consumption, contributes significantly to our carbon footprint. Correlation and regression analyses have shown this connection. In the agricultural phase, the use of more nitrogen and phosphate fertilizers leads to more carbon emissions. At this level, it is important

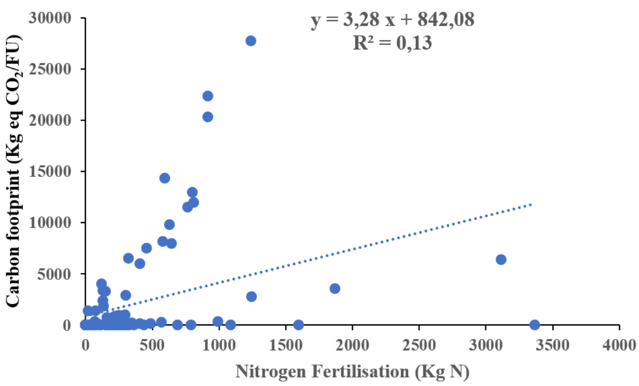


*Figure 9: Scatter plot with a linear regression curve illustrating the relationship between the carbon footprint and the Nitrogen fertilization (case of crop-based industries products) (FU stands for functional unit)*

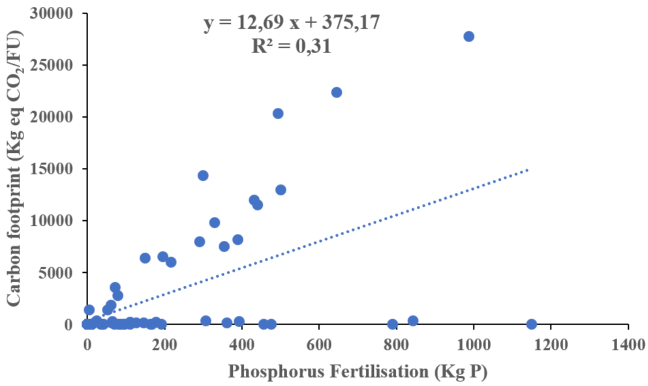


*Figure 10: Scatter plot with a linear regression curve illustrating the relationship between the carbon footprint and the Phosphorus fertilization (case of crop-based industries products) (FU stands for functional unit)*

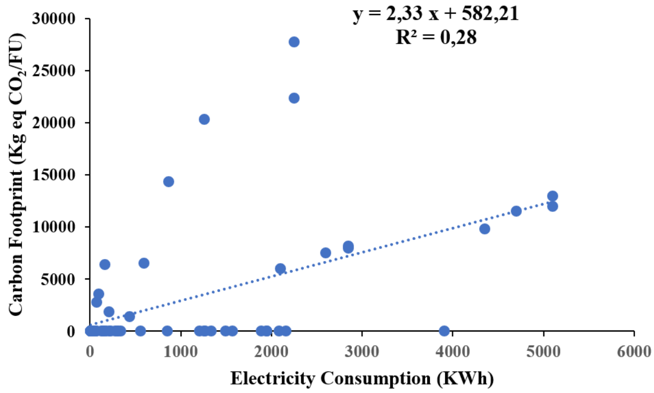


*Figure 11: Scatter plot with a linear regression curve illustrating the relationship between the carbon footprint and the electricity consumption (case of crop-based industries products) (FU stands for functional unit)*

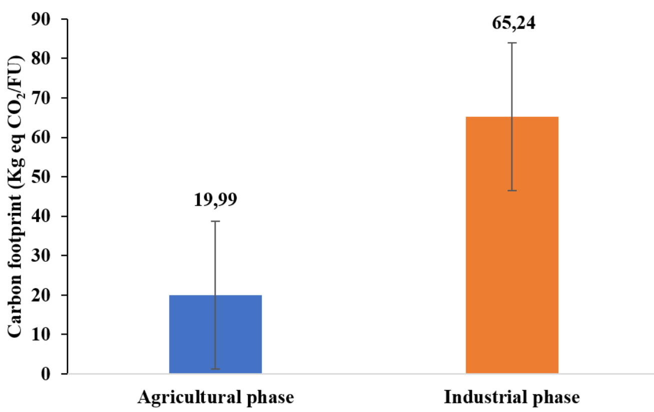


*Figure 12: Average carbon footprint values (kg CO2 eq./FU) for crop-based industries products. For these products, the carbon footprint is subdivided into an agricultural carbon footprint and an industrial carbon footprint (FU stands for functional unit)*

to study, for future work, the need to detail the relationship of other agricultural production components with the carbon footprint such as tillage and irrigation as well as plant protection treatments. In the same vein, for animal products, the information collected from the papers was not sufficient to determine the production components with a high impact on the carbon footprint. The best possible approach to study and analyze the carbon footprint of plant-based products is to provide a detailed description of the two sub-footprints that create it, i.e. H. the upstream agricultural activities and the downstream industrial activities. It is necessary to thoroughly determine the inputs of the agricultural phase and also integrate the part related to carbon sequestration by the soil and study the details of chemical fertilization (fertilizer production, transportation to the farm, use, and storage if used, transport of workers in manual application), study and understand the role of phytosanitary treatments (production of pesticides, purchase, and transport to the farm, use and storage, transport and movement of labor in manual treatments such as weed control), management of crop residues and manure and clear definition of the components of irrigation (transport and installation of equipment, type of pump, workload). The downstream industrial and processing phase provides the most detailed information possible about the industrial processes (energy requirements for transport + procurement + use/packaging and procurement + transport/waste management).

## CONCLUSION

This work illustrates the results of a meta-analysis that conducted scientific work between 2009 and 2023 to determine and calculate the carbon footprint of agro-industrial sectors. This meta-analysis aims to examine the calculation methods and production factors that emit the most carbon. The geographical distribution of carbon footprint studies shows a great contrast between continents. Europe and Asia (especially China) are the continents with the most work, and this is understandable considering the efforts that countries on these continents must make to reduce their emissions. On the other hand, it would make sense to do more work in Africa, especially since these are the countries that export agricultural products.

From a methodological perspective, life cycle analysis remains the dominant and most widely used approach to this type of work. Other methods exist and are still useful, such as the IPCC approach (particularly for work in the crop-based industries). For livestock/animal production there are on-farm emissions and off-farm emissions. The meta-analysis showed that emissions in the first category significantly exceed those in the second category. For crop-based industries, it is important to note that the industrial phase causes more emissions than the agricultural phase. Correlation and regression analyses show that electricity consumption and fertilization (nitrogen and phosphate) have a significant impact on the carbon footprint of crop sectors. In contrast to this finding, regression and correlation analysis failed to identify factors contributing to the carbon footprint of livestock sectors. Therefore, it will be interesting to conduct studies to identify the producer factors that contribute significantly to the carbon footprint of animal production.

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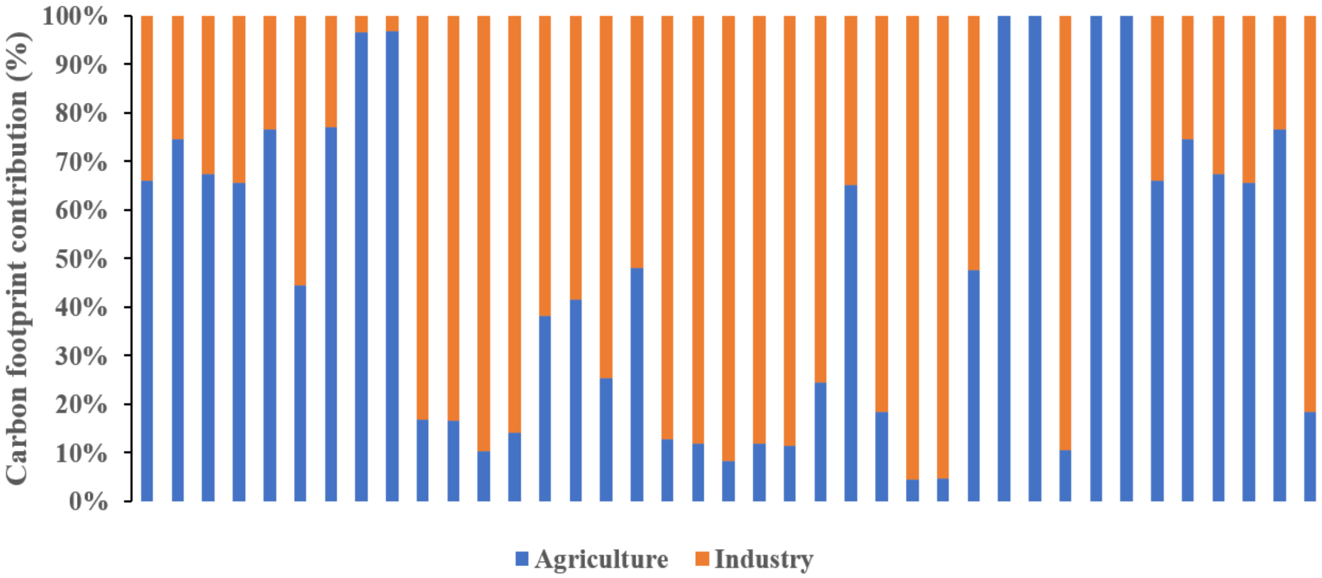


***Figure 13: Carbon footprint of plant-based products (agricultural vs. industrial phase)***

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