

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

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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 CO₂ eq/FU) is significantly lower than the on-farm average (3.02 ± 3.18 Kg CO₂ 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 CO₂eq/FU \pm 70.9) than the agricultural part (20.0 Kg CO₂eq/FU \pm 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 (CO₂) 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 CO₂ 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 CO₂ 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 (N₂O) is often the most significant emission for crop products and monogastric animal production, while methane (CH₄) 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 CO₂ 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 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 CO₂ 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 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 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:

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 ($0,69 \pm 0,79$ Kg CO₂ eq/functional unit) is lower meaningfully than the on-farm average ($3,02 \pm 3,18$ Kg CO₂ 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 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 CO₂/FU equivalent. In terms of fertilization, the consumption of 1 kg of nitrogen contributes to a carbon emission of 3.28 kg eq CO₂/FU. Likewise, when 1 kg of phosphorus is consumed, 12.69 kg of CO₂/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 CO₂ eq/FU ± 70.9) than the agricultural part (20.0 kg CO₂ 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%).

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; Kairé 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 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.

REFERENCES

- Abdul Rahman, M. H., Chen, S. S., Abdul Razak, P. R., Abu Bakar, N. A., Shahrin, M. S., Zin Zawawi, N., Muhamad Mujab, A. A., Abdullah, F., Jumat, F., Kamaruzaman, R., Saidon, S. A., Abdul Talib, S. A. (2019). Life cycle assessment in conventional rice farming system: Estimation of greenhouse gas emissions using cradle-to-gate approach. *Journal of Cleaner Production*, 212: 1526-1535.
- Abín, R., Laca, A., Laca, A., Díaz, M. (2018). Environmental assessment of intensive egg production: A Spanish case study. *Journal of Cleaner Production*, 179:160-168.
- Adewale, C., Reganold, J. P., Higgins, S., Evans, R. D., Carpenter-Boggs, L. (2019). Agricultural carbon footprint is farm specific: Case study of two organic farms. *Journal of Cleaner Production*, 229: 795-805.
- Alam, M. K., Bell, R. W., Biswas, W. K. (2019). Decreasing the carbon footprint of an intensive rice-based cropping system using conservation agriculture on the Eastern Gangetic Plains. *Journal of Cleaner Production*, 218: 259-272.
- Alhaji Ali, S., Tedone, L., Verdini, L., De Mastro, G. (2017). Effect of different crop management systems on rainfed durum wheat greenhouse gas emissions and carbon footprint under Mediterranean conditions. *Journal of Cleaner Production*, 140: 608-621.
- Aljazeera (2023). How much does Africa contribute to global carbon emissions? Available: www.aljazeera.com/news/2023/9/4/how-much-does-africa-contribute-to-global-carbon-emissions (28 April 2024).
- ALTECH (2020). Dairy efficiency by the numbers _ Hubbard Feeds. Available: www.hubbardfeeds.com/blog/dairy-efficiency-numbers (20 April 2024).
- Andrén, O., Lindberg, T., Boström, U., Clarholm, M., Hansson, A.-C., Johansson, G., Lagerlöf, J., Paustian, K., Persson, J., Pettersson, R., Schnürer, J., Sohlenius, B., Wivstad, M. (1990). Organic Carbon and Nitrogen Flows. *Ecological Bulletins*, 40: 85-126.
- Bajgai, Y., Yeshey, Y., De Mastro, G., Ghimiray, M., Chhogyel, N., Tshewang, S., Alhaji Ali, S.



- (2019). Influence of nitrogen application on wheat crop performance, soil properties, greenhouse gas emissions, and carbon footprint in central Bhutan. *Environmental Development*, 32: 100469.
- Bansal, S., Yin, X., Schneider, L., Sykes, V., Jagadamma, S., Lee, J. (2022). Carbon footprint and net carbon gain of major long-term cropping systems under no-tillage. *Journal of Environmental Management*, 307: 114505.
- Behera, S. K., Park, J. M., Kim, K. H., Park, H.-S. (2010). Methane production from food waste leachate in laboratory-scale simulated landfill. *Waste Management*, 30: 1502-1508.
- Belaud, J.-P., Espi, J. J. (2012). Life Cycle Assessment of olive oil production in France. September.
- Berton, M., Bittante, G., Zendri, F., Ramanzin, M., Schiavon, S., Sturaro, E. (2020). Environmental impact and efficiency of use of resources of different mountain dairy farming systems. *Agricultural Systems*, 181: 102806.
- Bertrand, S., Barnett, J. (2011). Standard method for determining the carbon footprint of dairy products reduces confusion. *Animal Frontiers*, 1: 14-18.
- Boettcher, R., Zappe, A. L., de Oliveira, P. F., Machado, Ê. L., Lawisch-Rodriguez, A. de A. Rodriguez-Lopez, D. A. (2020). Carbon Footprint of agricultural production and processing of tobacco (*Nicotiana tabacum*) in southern Brazil. *Environmental Technology and Innovation*, 18: 100625.
- Brunori, A. M. E., Sdringola, P., Dini, F., Ilarioni, L., Nasini, L., Regni, L., Proietti, P., Proietti, S., Vitone, A., Pelleri, F. (2017). Carbon balance and Life Cycle Assessment in an oak plantation for mined area reclamation. *Journal of Cleaner Production*, 144: 69-78.
- Carlin, J. B. (2000). Tutorial in biostatistics. Meta-analysis: Formulating, evaluating, combining, and reporting (multiple letters). *Statistics in Medicine*, 19: 753-759.
- Chen, X., Ma, C., Zhou, H., Liu, Y., Huang, X., Wang, M., Cai, Y., Su, D., Muneer, M. A., Guo, M., Chen, X., Zhou, Y., Hou, Y., Cong, W., Guo, J., Ma, W., Zhang, W., Cui, Z., Wu, L., Zhang, F. (2021). Identifying the main crops and key factors determining the carbon footprint of crop production in China, 2001-2018. *Resources, Conservation, and Recycling*, 172 (May).
- Chen, X., Xu, X., Lu, Z., Zhang, W., Yang, J., Hou, Y., Wang, X., Zhou, S., Li, Y., Wu, L., Zhang, F. (2020). Carbon footprint of a typical pomelo production region in China based on farm survey data. *Journal of Cleaner Production*, 277: 124041.
- Cheng, K., Pan, G., Smith, P., Luo, T., Li, L., Zheng, J., Zhang, X., Han, X., Yan, M. (2011). Carbon footprint of China's crop production-An estimation using agro-statistics data over 1993-2007. *Agriculture, Ecosystems and Environment*, 142: 231-237.
- Cheng, K., Yan, M., Nayak, D., Pan, G. X., Smith, P., Zheng, J. F., Zheng, J. W. (2015). Carbon footprint of crop production in China: An analysis of National Statistics data. *Journal of Agricultural Science*, 153: 422-431.
- Čuček, L., Klemeš, J. J., Kravanja, Z. (2012). A review of footprint analysis tools for monitoring impacts on sustainability. *Journal of Cleaner Production*, 34: 9-20.
- Dabkienė, V., Baležentis, T., Štreimikienė, D. (2020). Calculation of the carbon footprint for family farms using the Farm Accountancy Data Network: A case from Lithuania. *Journal of Cleaner Production*, 262.

- Dalgaard, R., Schmidt, J., Flysjö, A. (2014). Generic model for calculating carbon footprint of milk using four different life cycle assessment modelling approaches. *Journal of Cleaner Production*, 73: 146-153.
- de Léis, C. M., Cherubini, E., Ruviaro, C. F., Prudêncio da Silva, V., do Nascimento Lampert, V., Spies, A., Soares, S. R. (2015). Carbon footprint of milk production in Brazil: a comparative case study. *International Journal of Life Cycle Assessment*, 20: 46-60.
- Delgado-Rodríguez, M., Ibero-Arenas, M. (2018). Systematic review and meta-analysis. *Medicina Intensiva*, 42: 444-453.
- Della Riva, A., Kristensen, T., Marchi, M., Kargo, M., Jensen, J., Cassandro, M. (2014). Carbon footprint from dairy farming system: comparison between Holstein and Jersey cattle in Italian circumstances. 18: 75-80.
- Devi, S., Singh, S. (2023). Soil Organic Carbon Sequestration in Dryland Soils to Alleviate Impacts of Climate Change BT - Enhancing Resilience of Dryland Agriculture Under Changing Climate: Interdisciplinary and Convergence Approaches (A. Naorem & D. Machiwal (eds.); pp. 221-245). Springer Nature Singapore.
- Dunuwila, P., Rodrigo, V. H. L., Daigo, I., Goto, N. (2022). Social impact improving model based on a novel social life cycle assessment for raw rubber production: A case of a Sri Lankan rubber estate. *Journal of Cleaner Production*, 338: 130555. 5
- Escribano, M., Elghannam, A., Mesias, F. J. (2020). Dairy sheep farms in semi-arid rangelands: A carbon footprint dilemma between intensification and land-based grazing. *Land Use Policy*, 95(January).
- Espinoza-Orias, N., Stichnothe, H., Azapagic, A. (2011). The carbon footprint of bread. *International Journal of Life Cycle Assessment*, 16: 351-365.
- Fernández-Lobato, L., García-Ruiz, R., Jurado, F., Vera, D. (2021). Life cycle assessment, C footprint and carbon balance of virgin olive oils production from traditional and intensive olive groves in southern Spain. *Journal of Environmental Management*, 293(February).
- Finnveden, G., Potting, J. (2014). Life Cycle Assessment (P. B. T.-E. of T. (Third E. Wexler (ed.); pp. 74-77). Academic Press.
- Fitton, N., Alexander, P., Arnell, N., Bajzelj, B., Calvin, K., Doelman, J., Gerber, J. S., Havlik, P., Hasegawa, T., Herrero, M., Krisztin, T., van Meijl, H., Powell, T., Sands, R., Stehfest, E., West, P. C., Smith, P. (2019). The vulnerabilities of agricultural land and food production to future water scarcity. *Global Environmental Change*, 58: 101944.
- Flysjö, A. (2011). Potential for improving the carbon footprint of butter and blend products. *Journal of Dairy Science*, 94: 5833-5841.
- Flysjö, A., Henriksson, M., Cederberg, C., Ledgard, S., Englund, J. E. (2011). The impact of various parameters on the carbon footprint of milk production in New Zealand and Sweden. *Agricultural Systems*, 104: 459-469.
- Flysjö, A., Thrane, M., Hermansen, J. E. (2014). Method to assess the carbon footprint at product level in the dairy industry. *International Dairy Journal*, 34: 86-92.
- Gan, Y., Liang, C., Wang, X., McConkey, B. (2011). Lowering carbon footprint of durum wheat by diversifying cropping systems. *Field Crops Research*, 122: 199-206.

- Gao, N., Wei, Y., Zhang, W., Yang, B., Shen, Y., Yue, S., Li, S. (2022). Carbon footprint, yield and economic performance assessment of different mulching strategies in a semi-arid spring maize system. *Science of The Total Environment*, 826: 154021.
- Granato, G., Fischer, A. R. H., van Trijp, H. C. M. (2022). The price of sustainability: How consumers trade-off conventional packaging benefits against sustainability. *Journal of Cleaner Production*, 365: 132739.
- Gruber, L. M., Brandstetter, C. P., Bos, U., Lindner, J. P., Albrecht, S. (2016). LCA study of unconsumed food and the influence of consumer behavior. *The International Journal of Life Cycle Assessment*, 21: 773-784.
- Gutiérrez-Peña, R., Mena, Y., Batalla, I., Mancilla-Leytón, J. M. (2019). Carbon footprint of dairy goat production systems: A comparison of three contrasting grazing levels in the Sierra de Grazalema Natural Park (Southern Spain). *Journal of Environmental Management*, 232: 993-998.
- Gütschow, J., Jeffery, M. L., Gieseke, R., Gebel, R., Stevens, D., Krapp, M., Rocha, M. (2016). The PRIMAP-hist national historical emissions time series. *Earth System Science Data*, 8: 571-603.
- Hallström, E., Bergman, K., Mifflin, K., Parker, R., Tyedmers, P., Troell, M., Ziegler, F. (2019). Combined climate and nutritional performance of seafoods. *Journal of Cleaner Production*, 230: 402-411.
- Hansen, J., Ruedy, R., Sato, M., Lo, K. (2010). Global surface temperature change. *Reviews of Geophysics*, 48: 1-29.
- Hardelin, J., Lankoski, J. (2018). Land Use and Ecosystem Services. In *OECD Food, Agriculture and Fisheries Papers* (Issue 114).
- Hristov, A. N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Kijstra, J., Oostin, S. (2013). Mitigation of greenhouse gas emissions in livestock production - A review of technical options for non-CO₂ emissions (Issue Paper No. 177. FAO).
- Huang, W., Wu, F., Han, W., Li, Q., Han, Y., Wang, G., Feng, L., Li, X., Yang, B., Lei, Y., Fan, Z., Xiong, S., Xin, M., Li, Y., Wang, Z. (2022). Carbon footprint of cotton production in China: Composition, spatiotemporal changes and driving factors. *Science of The Total Environment*, 821: 153407.
- Huo, Y., Mi, G., Zhu, M., Chen, S., Li, J., Hao, Z., Cai, D., Zhang, F. (2024). Carbon footprint of farming practices in farmland ecosystems on the North and Northeast China plains. *Journal of Environmental Management*, 354: 120378.
- IPCC. (2006). IPCC Updates Methodology for Greenhouse Gas Inventories — IPCC. Available: www.ipcc.ch/2019/05/13/ipcc-2019-refinement/ (28 April 2024).
- Iribarren, D., Vázquez-Rowe, I., Hospido, A., Moreira, M. T., Feijoo, G. (2010). Estimation of the carbon footprint of the Galician fishing activity (NW Spain). *Science of the Total Environment*, 408: 5284-5294.
- Izadi, B., Mohebbi-Fani, M., Hosseinzadeh, S., Shekarforoush, S. S., Nazifi, S., Rasooli, A. (2021). Alteration of fatty acid profile of milk in Holstein cows fed *Bacillus coagulans* as probiotic: A field study. *Iranian Journal of Veterinary Research*, 22: 100-106.
- Jianyi, L., Yuanchao, H., Shenghui, C., Jiefeng, K., Lilai, X. (2015). Carbon footprints of food

production in China (1979-2009). *Journal of Cleaner Production*, 90: 97-103.

Johnson, N., Phillips, M. (2018). Rayyan for systematic reviews. *Journal of Electronic Resources Librarianship*, 30: 46-48.

Kairé, M., Sarr, B., Yaro Botoni, E. (2015). Enjeux des mécanismes de financement de l'adaptation au changement climatique pour l'Afrique de l'Ouest. *Semaine Du Sahel et de l'Afrique de l'Ouest/ EXPO 2015*, 13: 4-5.

Khaddour, L. A., Yeboah, S. K., Doodoo, J. K. B. T.-R. M. in E. S. and E. S. (2023). Ecological and Carbon Footprints of Cities. In *Life Cycle Assessment and Related Approaches*. Elsevier.

Lal, R. (2004). Soil carbon sequestration to mitigate climate change. *Geoderma*, 123: 1-22.

Lal, R., Follett, R. F., Stewart, B. A., Kimble, J. M. (2007). Soil carbon sequestration to mitigate climate change and advance food security. *Soil Science*, 172(12).

Lewis, A., Bher, A., Joshi, S., Daum, M., Auras, R. (2024). Assessing environmental trade-offs in packaging systems for infant formula delivery: A cradle-to-gate plus end-of-life life cycle assessment. *Sustainable Production and Consumption*, 47: 445-459.

Li, J., Yang, W., Wang, Y., Li, Q., Liu, L., Zhang, Z. (2018). Carbon footprint and driving forces of saline agriculture in coastally reclaimed areas of Eastern China: A survey of four staple crops. *Sustainability (Switzerland)*, 10(4).

Li, K., Zhao, M., Li, Y., He, Y., Han, X., Ma, X., Ma, F. (2024). Spatiotemporal Trends of the Carbon Footprint of Sugar Production in China. *Sustainable Production and Consumption*, 46: 502-511.

Liu, C., Plaza-Bonilla, D., Coulter, J. A., Kutcher, H. R., Beckie, H. J., Wang, L., Floc'h, J.-B., Hamel, C., Siddique, K. H. M., Li, L., Gan, Y. (2022). Chapter Six - Diversifying crop rotations enhances agroecosystem services and resilience. *Advances in Agronomy* 173: 299-335.

Luo, X., Guo, Y., Wang, R., Wang, N., Li, C., Chu, X., Feng, H., Chen, H. (2021). Carbon footprint of a winter wheat-summer maize cropping system under straw and plastic film mulching in the Loess Plateau of China. *Science of the Total Environment*, 794: 148590.

Maja, M. M., Ayano, S. F. (2021). The Impact of Population Growth on Natural Resources and Farmers' Capacity to Adapt to Climate Change in Low-Income Countries. *Earth Systems and Environment*, 5: 271-283.

Maximillian, J., Brusseau, M. L., Glenn, E. P., Matthias, A. D. (2019). Chapter 25 - Pollution and Environmental Perturbations in the Global System (M. L. Brusseau, I. L. Pepper, & C. P. B. T.-E. and P. S. (Third E. Gerba (eds.); pp. 457-476). Academic Press.

Mrówczyńska-Kamińska, A., Bajan, B., Pawłowski, K. P., Genstwa, N., Zmyślona, J. (2021). Greenhouse gas emissions intensity of food production systems and its determinants. *PloS One*, 16: e0250995.

Muralikrishna, I. V., Manickam, V. (2017). Chapter Five - Life Cycle Assessment (I. V Muralikrishna & V. B. T.-E. M. Manickam (eds.); pp. 57-75). Butterworth-Heinemann.

Musafiri, C. M., Kiboi, M., Ng'etich, O. K., Okoti, M., Kosgei, D. K., Ngetich, F. K. (2023). Carbon footprint of smallholder rain-fed sorghum cropping systems of Kenya: A typology-based approach. *Cleaner and Circular Bioeconomy*, 6: 100060.

Nayak, A. K., Tripathi, R., Debnath, M., Swain, C. K., Dhal, B., Vijaykumar, S., Nayak, A. D., Mohanty, S., Shahid, M., Kumar, A., Rajak, M., Moharana, K. C., Chatterjee, D., Munda, S., Guru, P., Khanam, R., Lal, B., Gautam, P., Pattanaik, S., Pathak, H. (2023). Carbon and water footprints of major crop production in India. *Pedosphere*, 33: 448-462.

Nemecek, T., Jungbluth, N., i Canals, L. M., Schenck, R. (2016). Environmental impacts of food consumption and nutrition: where are we and what is next? *The International Journal of Life Cycle Assessment*, 21: 607-620.

O'Brien, D., Brennan, P., Humphreys, J., Ruane, E., Shalloo, L. (2014). An appraisal of carbon footprint of milk from commercial grass-based dairy farms in Ireland according to a certified life cycle assessment methodology. *International Journal of Life Cycle Assessment*, 19: 1469-1481.

O'Brien, D., Capper, J. L., Garnsworthy, P. C., Grainger, C., Shalloo, L. (2014). A case study of the carbon footprint of milk from high-performing confinement and grass-based dairy farms. *Journal of Dairy Science*, 97: 1835-1851.

Omar, M. E. D., Nangia, V. (2023). On-farm water energy food carbon-footprint nexus index for quantitative assessment of integrated resources management for wheat farming in Egypt. *Water-Energy Nexus*, 6: 122-130.

Ouzzani, M., Hammady, H., Fedorowicz, Z., Elmagarmid, A. (2016). Rayyan-a web and mobile app for systematic reviews. *Systematic Reviews*, 5: 1-10.

Page, G., Ridoutt, B., Bellotti, B. (2012). Carbon and water footprint tradeoffs in fresh tomato production. *Journal of Cleaner Production*, 32: 219-226.

Parigiani, J., Desai, A., Mariki, R., Miner, R. (2011). The Carbon Footprint of an East African Forestry Enterprise. *Journal of Sustainable Development*, 4: 152-162.

Pattara, C., Salomone, R., Cichelli, A. (2016). Carbon footprint of extra virgin olive oil: a comparative and driver analysis of different production processes in Centre Italy. *Journal of Cleaner Production*, 127: 533-547.

Pereira, B. de J., Cecílio Filho, A. B., La Scala, N. (2021). Greenhouse gas emissions and carbon footprint of cucumber, tomato, and lettuce production using two cropping systems. *Journal of Cleaner Production*, 282: 124517.

Peter, C., Fiore, A., Hagemann, U., Nendel, C., Xiloyannis, C. (2016). 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. *International Journal of Life Cycle Assessment*, 21: 791-805.

Plassmann, K., Norton, A., Attarzadeh, N., Jensen, M. P., Brenton, P., Edwards-Jones, G. (2010). Methodological complexities of product carbon footprinting: a sensitivity analysis of key variables in a developing country context. *Environmental Science and Policy*, 13: 393-404.

Plaza-Bonilla, D., Nogué-Serra, I., Raffailac, D., Cantero-Martínez, C., Justes, É. (2018). Carbon footprint of cropping systems with grain legumes and cover crops: A case-study in SW France. *Agricultural Systems*, 167: 92-102.

Plaza, J., Revilla, I., Nieto, J., Hidalgo, C., Sánchez-García, M., Palacios, C. (2021). Milk quality and carbon footprint indicators of dairy sheep farms depend on grazing level and identify the different management systems. *Animals*, 11: 1-17.



Pleerux, N., & Aimkuy, N. (2021). Carbon footprint of mangosteen farm level evaluation in eastern Thailand. *Current Applied Science and Technology*, 21: 419-430.

Poore, J., Nemecek, T. (2018). Reducing food's environmental impacts through producers and consumers. *Science*, 360: 987-992.

Proietti, S., Sdringola, P., Desideri, U., Zepparelli, F., Brunori, A., Ilarioni, L., Nasini, L., Regni, L., Proietti, P. (2014). Carbon footprint of an olive tree grove. *Applied Energy*, 127: 115-124.

Rahman, M. M. (2023). Climate Change and Environmental Degradation: a Serious Threat To Global Security. *European Journal of Social Sciences Studies*, 8: 161-172.

Rana, R. L., Bux, C., Lombardi, M. (2023). Carbon footprint of the globe artichoke supply chain in Southern Italy: From agricultural production to industrial processing. *Journal of Cleaner Production*, 391: 136240.

Rinaldi, S., Barbanera, M., Lascaro, E. (2014). Assessment of carbon footprint and energy performance of the extra virgin olive oil chain in Umbria, Italy. *Science of the Total Environment*, 482-483: 71-79.

Robert Kiefer, L., Menzel, F., Bahrs, E. (2015). Integration of ecosystem services into the carbon footprint of milk of South German dairy farms. *Journal of Environmental Management*, 152: 11-18.

Roibás, L., Elbehri, A., Hospido, A. (2016). Carbon footprint along the Ecuadorian banana supply chain: Methodological improvements and calculation tool. *Journal of Cleaner Production*, 112: 2441-2451.

Ronga, D., Galligani, T., Zaccardelli, M., Perrone, D., Francia, E., Milc, J., Pecchioni, N. (2019). Carbon footprint and energetic analysis of tomato production in the organic vs the conventional cropping systems in Southern Italy. *Journal of Cleaner Production*, 220: 836-845.

Röös, E., Sundberg, C., Hansson, P. A. (2011). Uncertainties in the carbon footprint of refined wheat products: A case study on Swedish pasta. *International Journal of Life Cycle Assessment*, 16: 338-350.

Röös, E., Sundberg, C., Tidåker, P., Strid, I., Hansson, P. A. (2013). Can carbon footprint serve as an indicator of the environmental impact of meat production? *Ecological Indicators*, 24: 573-581.

Saavedra-Rubio, K., Thonemann, N., Crenna, E., Lemoine, B., Caliandro, P., Laurent, A. (2022). Stepwise guidance for data collection in the life cycle inventory (LCI) phase: Building technology-related LCI blocks. *Journal of Cleaner Production*, 366: 132903.

Samardzic, M., Vasin, J., Jajic, I., Andreeva, I., Latkovic, D., Vasenev, I. (2018). Environmental assessment of the greenhouse gases emission from poultry production in Russia's central region. *Journal of Agricultural Sciences, Belgrade*, 63: 261-270.

Santos, F. D., Ferreira, P. L., Pedersen, J. S. T. (2022). The Climate Change Challenge: A Review of the Barriers and Solutions to Deliver a Paris Solution. *Climate*, 10: 1-32.

Sharma, P., Bano, A., Singh, S. P., Srivastava, S. K., Singh, S. P., Iqbal, H. M. N., Varjani, S. (2023). Different stages of microbial community during the anaerobic digestion of food waste. *Journal of Food Science and Technology*, 60: 2079-2091.

Singh, R. L., Singh, P. K. (2017). *Global Environmental Problems BT - Principles and Applications of Environmental Biotechnology for a Sustainable Future* (R. L. Singh (ed.); pp. 13-41). Springer

Singapore.

Smith, P., Gregory, P. J. (2013). Climate change and sustainable food production. *Proceedings of the Nutrition Society*, 72: 21–28.

Sonesson, U., Davis, J., Ziegler, F. (2009). Food Production and Emissions of Greenhouse Gases different product groups (Issue 802).

Suardi, A., Bravo, I., Beni, C., Papetti, P., Leonardo Rana, R. (2024). Carbon footprint of hemp and sunflower oil in southern Italy: A case study. *Ecological Indicators*, 160: 111786.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Joliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J., Norris, G. (2004). System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. *Environmental Science & Technology*, 38: 657–664.

Sun, T., Feng, X., Lal, R., Cao, T., Guo, J., Deng, A., Zheng, C., Zhang, J., Song, Z., Zhang, W. (2021). Crop diversification practice faces a tradeoff between increasing productivity and reducing carbon footprints. *Agriculture, Ecosystems and Environment*, 321: 107614.

Suuronen, P., Chopin, F., Glass, C., Løkkeborg, S., Matsushita, Y., Queirolo, D., Rihan, D. (2012). Low impact and fuel-efficient fishing-Looking beyond the horizon. *Fisheries Research*, 119–120: 135–146.

Uddin, M. E., Aguirre-Villegas, H. A., Larson, R. A., Wattiaux, M. A. (2021). 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. *Journal of Cleaner Production*, 298: 126720.

Uusitalo, V., Väisänen, S., Havukainen, J., Havukainen, M., Soukka, R., Luoranen, M. (2014). Carbon footprint of renewable diesel from palm oil, jatropha oil, and rapeseed oil. *Renewable Energy*, 69: 103–113.

Vasilaki, V., Katsou, E., Ponsá, S., Colón, J. (2016). Water and carbon footprint of selected dairy products: A case study in Catalonia. *Journal of Cleaner Production*, 139: 504–516.

Vergé, X. P. C., Maxime, D., Dyer, J. A., Desjardins, R. L., Arcand, Y., Vanderzaag, A. (2013). Carbon footprint of Canadian dairy products: Calculations and issues. *Journal of Dairy Science*, 96: 6091–6104.

Vinyes, E., Asin, L., Alegre, S., Gasol, C. M., Muñoz, P. (2018). Carbon footprint and profitability of two apple cultivation training systems: Central axis and Fruiting wall. *Scientia Horticulturae*, 229: 233–239.

Xi, M., Xu, Y., Zhou, Y., Wu, C., Tu, D., Li, Z., Sun, X., Wu, W. (2024). Energy use and carbon footprint in response to the transition from indica rice to japonica rice cropping systems in China. *Energy*, 299:131408.

Xu, C., Chen, Z., Ji, L., Lu, J. (2022). Carbon and Nitrogen Footprints of Major Cereal Crop Production in China: A Study Based on Farm Management Surveys. *Rice Science*, 29: 288–298.

Xu, X., Lan, Y. (2016). A comparative study on carbon footprints between plant- and animal-based foods in China. *Journal of Cleaner Production*, 112: 2581–2592.

Xu, X., Lan, Y. (2017). Spatial and temporal patterns of carbon footprints of grain crops in China. *Journal of Cleaner Production*, 146: 218–227.



Xu, X., Sharma, P., Shu, S., Lin, T.-S., Ciaia, P., Tubiello, F. N., Smith, P., Campbell, N., Jain, A. K. (2021). Global greenhouse gas emissions from animal-based foods are twice those of plant-based foods. *Nature Food*, 2: 724-732.

Yan, M., Pan, G. X., Chen, L. (2012). An analysis of carbon footprint of vegetable production in Jiangsu, China. *Acta Horticulturae*, 958: 203-210.

Yang, X., Gao, W., Zhang, M., Chen, Y., Sui, P. (2014). Reducing agricultural carbon footprint through diversified crop rotation systems in the North China Plain. *Journal of Cleaner Production*, 76: 131-139.

Zhang, D., Shen, J., Zhang, F., Li, Y., Zhang, W. (2017). Carbon footprint of grain production in China. *Scientific Reports*, 7: 1-11.

Zhao, Y., Wang, L., Lei, X., Wang, B., Cui, J., Xu, Y., Chen, Y., Sui, P. (2021). Reducing carbon footprint without compromising grain security through relaxing cropping rotation system in the North China Plain. *Journal of Cleaner Production*, 318: 128465.

References