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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 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_2eq/FU ± 70.9) than the agricultural part (20.0 Kg CO_2eq/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 (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 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 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 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 ± 0,79 Kg CO2 eq/functional unit) is lower meaningfully than the on-farm average (3,02 ± 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; 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 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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