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Are short agri-food chains environmentally sustainable? Reflections on the case of amaranth in Mexico City

Cadenas cortas agroalimentarias ¿ambientalmente sostenibles? Reflexiones desde el caso del amaranto en la Ciudad de México

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Abstract

Short agri-food supply chains [SASC] have been presented as an environmentally sustainable alternative to the traditional food production, processing, and commercialization models due to their minimal intermediation and shortened supply chains. This structure can theoretically reduce greenhouse gas emissions [GHG] and mitigate the negative environmental impacts of agri-food activities. This is particularly relevant in urban settings such as Mexico City [CDMX], where much of the food demand is concentrated and often relies on peri-urban production. In CDMX, amaranth is considered an identity-defining food of the capital's peri-urban region. It has significant nutritional value and agri-food potential, it preserves pre-Hispanic roots, and is cultivated within the city's agricultural spaces. Through life cycle analysis, it was identified that while the proximity of peri-urban production and commercialization spaces may reduce GHG emissions, the processing stage presents the greatest CO_2 emissions and requires more sustainable and innovative popping techniques. These techniques should allow for better fuel efficiency or the incorporation of renewable energy methods. Otherwise, the potential benefits of SASC may be outweighed by the negative effects of GHG emissions.

Keywords: amaranth, greenhouse gases, peri-urban, short agrifood chain, sustainability.

Resumen

Las cadenas cortas agroalimentarias [CCA] se han presentado como alternativas ambientalmente sostenibles a la actividad tradicional de producción, transformación y comercialización de alimentos debido a su naturaleza de mínima intermediación y acortamiento de eslabones, lo que teóricamente puede generar una disminución en las emisiones de gases de efecto invernadero [GEI] y contribuir a minimizar los efectos negativos ambientales de la actividad agroalimentaria. Esto es de especial interés en ámbitos urbanos como: la Ciudad de México [CDMX], los cuales concentran gran parte de la demanda de alimentos y recurren a la producción periurbana para satisfacer dichas demandas. En la CDMX, el amaranto es considerado un alimento identitario de la región periurbana de la capital, con un amplio valor nutricional y potencial agroalimentario, que conserva raíces prehispánicas y que se cultiva en el espacio agrícola de la urbe. En este sentido, se logró identificar, mediante premisas del análisis del ciclo de vida, que si bien la proximidad de los espacios de producción y comercialización periurbana puede contribuir a disminuir la emisiones de GEI en esta cadena, el eslabón de procesamiento (el cual resultó ser es el eslabón que mayor emisión de CO_2 presentó en la cadena) requiere de implementar técnicas de reventado más sostenibles e innovadoras y que permitan un mejor aprovechamiento de los combustibles o la inserción de métodos basados en energías renovables; de otra forma, los posibles beneficios de las CCA podrían verse opacados por los efectos negativos de los GEI.

Palabras clave: amaranto, cadena corta agroalimentaria, gases de efecto invernadero, periurbano, sostenibilidad.

1. Introduction

In recent years, the food consumption trend has been shifting towards the promotion of "local" products, as well as production, processing, and consumption alternatives that originate from linking small-scale production with proximity to the final consumer, contributing to more sustainable future agri-food systems (Cui et al., 2024). In this context, the concept of short agri-food supply chains [SASC] has emerged strongly, presenting these as alternatives that counter both mass and heterogeneous food production, helping to reduce the environmental impact of agri-food activities by shortening supply chains and promoting more sustainable eating (Aubry & Kebir, 2013; Organización de las Naciones Unidas para la Alimentación y la Agricultura [FAO], 2016). These SASCs also help reduce the flows, transfers, distances, and transactions required for agri-food activities, making the physical proximity that characterizes them, bring about- as a result- a reduction of the carbon footprint (FAO, 2017).

SASCs can be defined as territorial (local) systems in which the stages of —production, processing, distribution, and consumption—, that a food product goes through, are interconnected through a limited number of actors from its origin to its arrival to the final consumer (FAO, 2016; Padilla & Oddone, 2014). According to Canfora (2016), these systems are structured through relationships of cooperation, geographical and social proximity, and focus on local development. In this sense, geographical proximity, in relation to food, provides identity and rootedness of producers to their places of origin, "reinforces the appreciation of foods with territorial roots and fosters trust bonds, also producing cognitive proximity as a common framework for understanding and interaction among socio-territorial actors" (Torres Salcido, 2022, pp. 141-142, authors' translation); at the same time, this "valorization" allows for the integration of foods into specialty markets (FAO, 2016), favoring higher income for local producers.

SASCs have been associated with environmental benefits as they are linked to the reduction of carbon dioxide [CO_2] emissions, which is a greenhouse gas [GHG], whose accumulation as a pollutant in the atmosphere causes severe negative environmental effects that contribute to global warming and affect human health. In SASCs, the shortening of transport distances, the promotion and conservation of bio- and agrobiodiversity, and the encouragement of peri-urban agriculture (Canfora, 2016), which make the supply of "in situ" food from the urban-rural fringe possible (Benis & Ferrão, 2017, p. 785).

Likewise, these chains promote the creation of social capital based on relationships of trust and the symmetrical exchange of information, both among producers and from them to consumers (Romero-López & Ramos, 2017). Therefore, these SASCs have enjoyed significant recognition, and validation as more sustainable alternatives[1] when compared to globalized agri-food chains; particularly, regarding the element of proximity between their stages, and given the recent importance that both consumers and public and private actors have attributed to the externalities of these systems (Cui et al., 2024). In this sense, "Shortening the agri-food chain is being presented in many commercial schemes as a synonym of sustainability and also healthy products. In this sense, although short food supply chains are associated with better product quality, social supportive production and fair commercial practices, these characteristics do not develop automatically" (Muñoz Torres et al., 2022).

However, despite the apparent "benefits" of structures such as SASCs, their sustainability is not always guaranteed. As emphasized by Majewski et al. (2020), in their analysis of short and long distribution chains in European countries, recent results showed lower environmental impacts (in terms of energy consumption, pollution, and GHG emissions) for long chains compared to short chains. In this regard, it is considered important to test the premise of SASC sustainability, as well as to question the functionality of these structures in shortening production stages, especially given the hegemonic paradigm surrounding SASCs that may lead to an incorrect "romanticization" of the concepts, by intrinsically linking these to environmental sustainability, which is the main focus of this work.

It is worth mentioning that the study of SASCs in cities has been approached from various angles; for

[1] Exemplifying this phenomenon is the growing emphasis on quantifying the kilometers traveled from the origin of a food product to the point of consumption to determine its carbon footprint or food miles (Lang & Irving, 2006).

example, in relation to the pillars that support food security (Martínez Salvador et al., 2021), or with regard to the solidarity economy and fair trade as drivers of the transition of urban food systems (Chiffoleau et al., 2019); and also through the integration of geographical and organizational proximity and the added value derived from food production in short supply chains (Comisión Económica para América Latina y el Caribe [CEPAL], FAO, & Instituto Interamericano de Cooperación para la Agricultura [IICA], 2014; Jarzębowski et al., 2020). These studies address the revitalization of the local scale through alternative marketing spaces, for instance SASCs and the economic effects they bring, such as access to fairer and more solidarity-based marketing spaces, or the possibility of maintaining added agricultural value in the territories of origin.

With this in mind, the present study selected Mexico City as the study area, where, even though the demand for food corresponds to the high population density and it is one of the main consumption centers in the country, it is considered that in this peri-urban space, scenarios like the one mentioned by Ávila-Sánchez (2024), in which "[…] conventional production modalities prevail, but alternative forms of solidarity consumption and the production of healthy food multiply […]" (p. 5, authors' translation), can coexist. Likewise, seems relevant to reflect on this area, since the city can produce, especially in peri-urban spaces, up to 20% of the food consumed (Dieleman, 2017), and this figure demonstrates the city's dependence on production from other regions, thus highlighting the great importance of promoting peri-urban agriculture systems that contribute to the production and distribution of local foods.

The focus of this study was designated in this context, as the cultivation of amaranth and its agri-food chain is considered an emblematic food of Mexico city, and is locally recognized for reflecting a broad peri-urban tradition[2], where amaranth is highly valued for its nutritional content (Moran Bañuelos et al., 2014), properties, and potential for productive diversification. Similarly, amaranth is cultivated, processed, and marketed under family and local production systems, where producers are unique as they participate in most of the stages in the value chain, that is to say, they demonstrate a multi-chain dynamic, therefore helping to reduce intermediaries. Within this context, it is worth noting that amaranth is produced in small-scale family units, especially in the town of Santiago Tulyehualco in the Xochimilco district (Martínez Salvador et al., 2022), with partial plantings that occur on lands belonging to conservation soils[3] and has unique characteristics that give it a sense of a short supply chain[4]. Likewise, amaranth in Mexico City is the materialization of a food offer with differentiated characteristics due to its roots in the territory as well as its nutraceutical attributes and productive diversification capacity, which can positively impact the food supply; however, little is known about the environmental impact of this productive activity. Therefore, in the face of a growing trend of increasingly conscious and informed consumers concerning the impacts of agricultural activity on sustainability, and given the presence of a 'food citizen' who promotes the consumption of local products (Renting et al., 2012), reflecting on CO_2 emissions linked to the amaranth value chain is also relevant.

It is worth noting that, given certain questions surrounding the environmental dimension in SASCs, Folinas et al. (2013) and Elshaer et al. (2023) propose that this dimension should be evaluated from a Life Cycle Analysis (LCA) perspective, as well as through the estimation of the ecological footprint, which is carried out by identifying and quantifying the carbon footprint of the chains, that is, CO_2 emissions, which helps to quantify emissions in relation to food transportation. In this context, Mundler and Rumpus (2012) emphasize the importance of segmenting value chains, as in this case study of amaranth, having a more precise understanding of the environmental impact.

Considering the above, this article aims to analyze the SASC of amaranth in the peri-urban area of Mexico City, evaluate the environmental impact in terms of GHG emissions (CO_2e), and propose recommendations to enhance its functionality as an environmentally more sustainable alternative to traditional chains, based on recovering some elements of the LCA and applying interviews with producers in the amaranth chain. This analysis addresses the study of the amaranth SASC by retrieving premises from value chains,

[2] Amaranth and amaranth products have been recognized as Intangible Cultural Heritage of Mexico City. (Secretaría de Agricultura y Desarrollo Rural [SADER], 2020a)

[3] Conservation soils are geographical areas that, due to their contribution of environmental services to biodiversity for the benefit of the population of Mexico city, are protected by government agencies such as the Ministry of the Environment (Jujnovsky et al., 2022).

[4] The relevance of using the SASC analytical framework in analyzing peri-urban amaranth in the city arose from the presentation of members linked to the Amaranto Product System organization of Mexico City at a thematic SASC seminar for cities, organized by the Institute of Geography of the Universidad Nacional Autónoma de México [IG UNAM] on August 17, 2017. The speakers emphasized the centrality of productive activities around the specificity of amaranth in a peri-urban region, as well as the involvement of agricultural producers throughout the various stages of the value chain, the example of the approach aimed at agroecological production and the identity representation of the food 'amaranth' for a community. These elements provided the starting point to analyze this food product from the SASC approach.

taking into account the different stages from primary production to commercialization.

It is worth highlighting that in the field of the amaranth chain, it is important to consider premises around added value and value chains, which are structured through various stages, inputs, actions, and activities, starting from the production stage to the final consumption in order to add value to production (Padilla and Oddone, 2014). This is of special importance for those SASCs where the primary actors, or producers, such as in the case of amaranth, lead practically all the stages in the chain, and in this study, they are seen as "multi-chain" producers".

This work is structured as follows: The first section addresses the SASC of amaranth as an agricultural crop, its main actor, and the supply chains that comprise it; the second explains the materials and methods, drawing on premises from the Life Cycle Analysis [LCA] from which phases, objectives, and energy inventory are identified in order to determine the carbon footprint [HCO_2] of the functional unit (that is, amaranth) and the total annual emissions related to the LCA of amaranth. The third section includes the results, which present the HCO_2 by LCA analysis stages; likewise, the discussion delves into identifying the stage with the greatest environmental impact, and a comparison of results with other foods is made. Finally, a sensitivity analysis is proposed to suggest alternatives for reducing the HCO_2. The fourth section presents conclusions and final recommendations.

2. A brief look at the amaranth SASC in Mexico City

Amaranth (*Amaranthus* spp.) is a crop with great traditional value and high drought resistance, making it highly adaptable to extreme water conditions. This crop, considered a pseudocereal (Figure 1), is produced in the central region of the country, with a particular tradition of production in Mexico City since the precolonial era, and according to anthropological evidence, it has existed in Mexico for 4,000 years (Mapes, 2015).

In Mexico city, in 2017, a little over 139 tons of amaranth were produced, with a production value of 3,246 thousand pesos (Sistema de Información Agroalimentaria de Consulta [SIACON], 2023). Amaranth is cultivated in the southeastern area of the city, especially in the municipalities of Milpa Alta, Tláhuac, and Xochimilco. The latter is of particular interest for this study because there, amaranth is a key crop for the preservation of the ecosystem of the Teuhtli volcanic hill, as well as being a pillar of the economic and cultural activities of the locality of Santiago Tulyehualco, the main study area. It is worth noting that amaranth is highly versatile in the preparation of various food products, is gluten-free, and has gained recognition as a superfood due to its high nutritional value, including fiber, protein, and minerals (Cano, 2022).

The amaranth producers in the study area, that due to the previously mentioned dynamics (participate in almost all stages of the value chain), can be understood as "multi-chain," are made up of families operating under micro, small, and medium-sized business schemes, where the household is also used as a point of sale on many occasions, reducing the involvement of third parties in the development of certain activities, from harvesting and processing to marketing the amaranth.

The amaranth SASC in Mexico City operates based on a series of processes or supply chains in a flow,

Figure 1. Amaranth seeds in the hand of a producer.

Source: Picture taken by Pilar Ortíz Martínez which are connected as shown in Figure 2.

In the first and second stages, we find primary production activities that involve planting and harvesting activities, respectively; the processing of the amaranth seed is achieved in the transformation stage, with the product "popped amaranth" being the most commonly obtained good for the preparation of other products, and from which the amaranth grain is subjected to a thermal process, thereby "toasting" the seed. From popped amaranth and various ingredients, products such as granolas and "alegrías," a typical sweet representative food of the Santiago Tulyehualco production area in Xochimilco, can be obtained, among others (Martínez Salvador et al., 2022). A fourth stage related to marketing allows us to identify that the productive activity of amaranth aligns with the theoretical premises of SASC, since agricultural production, framed within a specific territory, maintains a geographical closeness between the production site and the urban end market, under peri-urban dynamics that could favor marketing without intermediaries through farmers' markets or direct sales to peri-urban consumers. In this sense, it is worth noting that, in the Xochimilco area, farmers' fairs are another initiative for direct commercial interaction between amaranth producers and consumers in the locality, with the most representative event of this crop being the one mentioned by (Tolentino Martínez & Martínez Salvador, 2021), the National Amaranth and Olive Fair, where the local culinary offerings are showcased.

3. Materials and Methods

For the analysis of the SASC of amaranth and the calculation of its CO_2 emissions at each stage, some premises from Life Cycle Analysis [LCA] are taken, which is a tool that allows identifying and evaluating the use of materials and energy, as well as assessing opportunities for environmental improvement throughout the entire life cycle of a system (Azapagic & Clift, 1999; Keoleian & Spitzley, 2006) or as in the case of this work, in an agri-food chain. This study required the collection of primary data from the chain, which was carried out using techniques such as participant observation and semi-structured interviews, as well as on-site visits in fieldwork, which took place between September and November 2017 within the framework of the main author's doctoral research. During this period, various multi-chain producers were consulted, and 32 semi-structured interviews were conducted. The selection criterion for the interviewees was through a snowball process, as the initial contacts in the area occurred during various visits to the town of Santiago Tulyehualco, where representatives of the "Sistema Producto Amaranto A.C." were initially interviewed, and information was obtained about the location of other producers.

The interviews were divided into four sections, which collected information on the following topics: organizational information of the amaranth SASC producer; energy inputs identified in the stages of primary production, harvest, and post-harvest; energy and fuel inputs identified in the processing stage; fuels identified in the marketing stage (for more details, see Table 1). These interviews provided key information for identifying CO_2 emissions at the SASC stages, to define environmental burdens in the value chain, to understand the most critical pollution stage identified, and to form reflective positions, as well as extending recommendations based on the responses obtained from the interviewee.

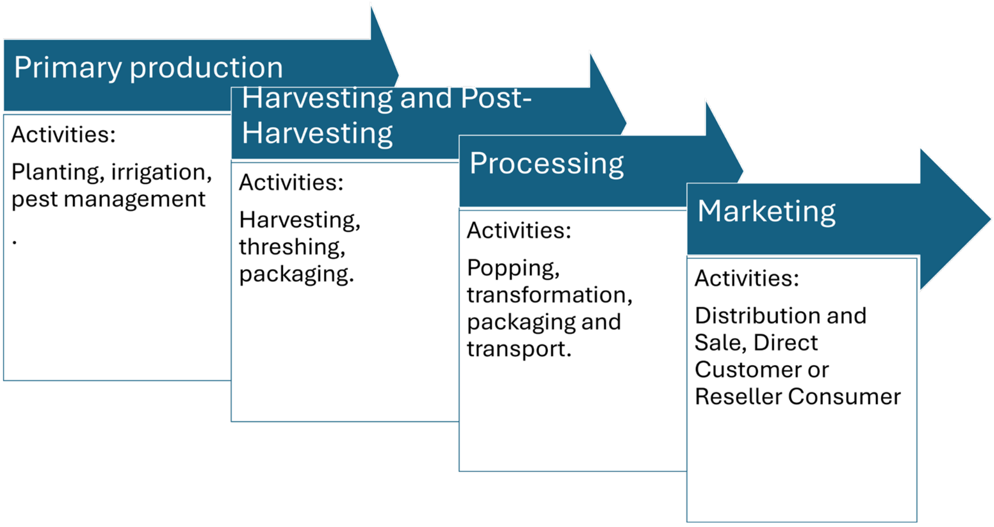

Figure 2. Outline of the Amaranth SASC in Mexico City.

Source: Based on Tolentino Martínez and Martínez Salvador (2021) and Rodríguez-Fernández et al. (2019).

By making use of some premises of the LCA for the case of the amaranth SASC, the four following phases recommended by the International Standard ISO 14040:2006 were carried out: 1) defining the system [chain] boundaries and objectives; 2) data collection for the inventory analysis; 3) calculation of CO_2 emissions; 4) interpretation of results. These are described below:

1) Definition of system boundaries [chain] and objectives:

a) Definition of scope and objectives: the purpose of using this technique was to calculate the annual carbon footprint [kg CO_2e] and per kg of popped amaranth produced in the SASC of amaranth, by reflecting the nature of minimal intermediaries and the distance between the producer and the consumer, based on fossil energy inputs of direct emissions (International Standard ISO 14064-1:2018), within the system boundaries, which encompass from primary production to commercialization based on the data from the interviewees.

b) To define the data to be obtained in the inventory during the primary production, harvest, and post-harvest stages, the energy consumption for transportation that moves producers during planting, irrigation, pest management, and harvest transportation activities was considered, as well as the energy used for threshing machinery and tractors. For the seed processing stage, information was requested from interviewees about the amounts of fuel used for amaranth roasting. In commercialization, the energy used to transport amaranth to a single local client with a weekly round trip was considered. These stages were chosen because they represent the main flow of energy in this SASC and capture the most significant emissions that are under the direct control of the multi-chain stakeholders.

c) SASCs, being consistent with their objectives of local production and distribution, exclude certain stages that are more relevant in other supply chains, such as the production of agricultural inputs. For example, the production of chemical fertilizers is a process that is outside the local producer's control, and its use, in the case of the amaranth SASC, would not provide relevant information that the chain actors could mitigate since the use of chemical fertilizers is not representative. On the other hand, final disposal is a stage that is also outside the direct control of the production and marketing chain. Actions such as managing product waste make this stage highly variable and complex to quantify.

d) In this regard, the analysis considered the energy consumption from fossil sources (gasoline, diesel, LPG, and coal) over an annual operational cycle (Salomone & Ioppolo, 2012) within the short agri-food value chain, with a total production volume of 138 t of amaranth, and the functional unit[5] was defined based on 1 kg of popped amaranth, according to other reported agri-food chain studies (Cucurachi et al., 2019; Iglesias, 2005; Petti et al., 2006).

e) Since the aim is to measure the CO_2 emissions of the amaranth SASC, this analysis corresponds to the impact category: climate change, measured by the equivalent of CO_2 emitted[6] and the quantitative representation that classifies and measures the environmental impact called the "category indicator"[7]. Likewise, the scope of analysis of the amaranth SASC is determined by the four main stages that characterize amaranth activities and range from primary production to marketing (Figure 3).

In Figure 3, from left to right, the stages representing the scope of the SASC are shown. In the first row, the stages of the amaranth chain are displayed (establishing the limits of the analyzed system); at a second level, the details of the activities carried out at the stages by the producers are presented, while at a third level, the fossil-based energy sources used at each stage are detailed.

2) Data collection for inventory analysis:

a) Inventory analysis within the SASC of amaranth. This phase was carried out by detailing the fuels reported by the producer at the different stages that make up the chain. By stage (Table 1), the second column indicates the energy inputs based on the requirements of machinery and/or vehicle equipment for each stage; the third column shows the respective standard unit of measurement for the energy; while the fourth column indicates the

[5] The functional unit is defined as the function or service provided by the system under study and serves as a basis for comparing different alternatives (Cucurachi et al., 2019).

[6] Emissions of kg CO_2e (carbon dioxide equivalent emissions) is defined as "The amount of carbon dioxide emission that would cause the same integrated radiative forcing, over a given time horizon, as an emitted amount of a greenhouse gas or a mixture of greenhouse gases" (IPCC, 2013, p. 191). CO_2 is the reference greenhouse gas for measuring other GHGs because it remains in the atmosphere for up to 100 years, according to its global warming potential (GWP) of 1. This allows for the consideration of other GHGs within its metric, referring to the use of kg CO_2e.

[7] The category indicator corresponds to the metric used to measure environmental impact based on its contribution to the problem (Rodrigues Viana et al., 2023). In this case, the indicator value provides the result in kg CO_2e and considers the category of environmental impact related to climate change.

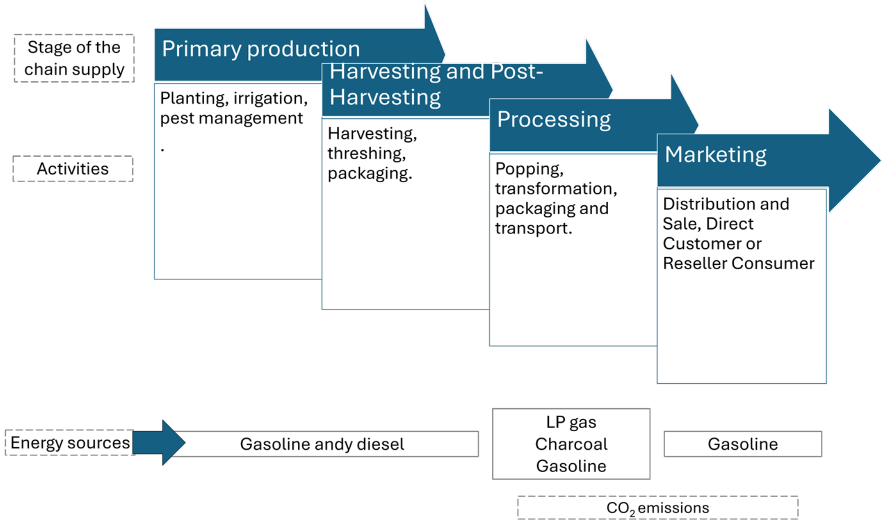

Figure 3. Scope of analysis: The amaranth SASC.

Based on Del Rosario et al. (2021) and Tolentino Martínez and Martínez Salvador (2021).

unit of measurement for the emission of the energy factor [kg CO_2e][8], and the relevant explanation for each stage regarding the formation of the energy input inventory is found in the fifth column.

3) CO_2 Emissions Calculation:

a) The analysis of this LCA was carried out based on an annual production of 138 t of amaranth, and as shown in Table 1, the inventory of energy inputs was composed of fossil fuel sources used at each stage of production. Once the energy inputs are considered, the amount of pollutants for each type of energy is determined by multiplying by the GHG emission factors for the different types of fossil fuels (INECC, 2014). The result obtained will represent the annual impact of the amaranth LCA in terms of carbon dioxide equivalent emissions, expressed in kg CO_2e.

b) Impact analysis: The mathematical formulation for calculating CO_2e emissions considered in this study is that proposed by Keoleian and Spitzley (2006), which expresses the total CO_2e emissions impact [*I*] by summing all the results for each stage of the CO_2e emissions based on the energy quantities from the inventory (equation [1]), where cf_i is the emission factor for fossil fuel sources for Mexico City; and e_i is the energy quantity from the inventory.

$$I = \sum cf_i e_i \qquad [1]$$

When obtaining the total CO_2e emission impacts corresponding to the analysis of the entire amaranth LCA, these results are equated in relation to the functional unit. The calculation of the functional unit is carried out based on the total energy quantities of each stage of the inventory (LCA chains) and the corresponding proportional relationship is established for 1 kg of amaranth (Iglesias, 2005). Then, it is multiplied by the CO_2 emission factor of each energy source, and the result obtained will be kg CO_2e per kg of amaranth (Tables 3, 4 and 5).

4) Interpretation of results: In this phase, the results of the inventory analysis are combined with the environmental impact analysis, and it is determined in which phase, or in this case, stage of the chain, the highest CO_2 emission is generated. Considering that the impact category to which CO_2 emissions correspond in all LCAs is that of climate change (International Standard ISO 14040:2006), the stage with the greatest environmental impact will also be the one that contributes most to this impact category.

On the other hand, a sensitivity analysis is conducted based on the proposal of three scenarios (10% reduction; 20% reduction; 10% increase), with the aim of identifying possible effects of changes in CO_2 emissions (López-Cruz et al., 2012; Rodrigues Viana et al., 2023) in response to changes in energy consumption.

Likewise, a literature review was carried out to identify other short agri-food chains where the carbon footprint indicator (with CO_2 emissions as a variable) was the main element of analysis, from which it was possible to generate a comparative reflection on the amaranth SASC.

[8] Fossil fuels possess an emission factor (see Table 2, column 4) corresponding to each energy source. When these factors are multiplied by the amounts of energy reported in the inventory, the result is the amount of pollutant emissions in kg CO_2e.

Table 1. Reported inventory of annual energy inputs in the amaranth SASC of Mexico City and their conversion factor to CO_2e emissions.

Stage	Energy input (*i*)	Unit of measurement (e_i)	Energy emission factor (cf_i)	Explanation
Primary production	Gasoline (vehicles for planting, irrigation, pest control) Diesel (harvesting machinery)	Liters	kg CO_2e L^{-1} of gasoline	The result obtained from the sum of liters of gasoline or diesel used in this stage is reported based on the annual agricultural production cycle by the 32 interviewees. The number of days of vehicle use for planting, irrigation, or crop management activities, the kilometers traveled, and the fuel used were consulted. In the case of machinery, the number of days each producer uses it and the amount of fuel required were consulted. Subsequently, the energy quantity in the inventory was multiplied by the corresponding emission factor for the type of fossil fuel (gasoline and diesel) to obtain the result in kg CO_2e (Table 2).
Harvesting	Diesel (machinery [threshing machine])	Liters	kg CO_2e L^{-1} of diesel	
Post-harvesting	Gasoline (harvest transportation)			
Processing	LPG (machinery or stoves for roasting the processed seed annually)	Kilograms	kg CO_2e kg^{-1} of LPG	In this stage, the quantification of fossil fuels: LPG and coal is corresponding to the transformation of 138 tons of amaranth. The energy quantity in the inventory for this section (kg of LPG and kg of coal) was obtained by asking each interviewee about the quantities of amaranth processed in a year, as well as the amount of LPG or coal used for processing per kilogram of amaranth.
	Coal (popping amaranth)	Kilograms	kg CO_2e kg^{-1} of coal	Subsequently, the quantification of energy sources is multiplied by the emission factor for the corresponding type of fossil fuel [LPG and coal] to obtain the pollutant emissions in kilograms of CO_2e (Table 2).
Marketing	Gasoline (transportation equipment for distribution of the "popped amaranth" product)	Liters	kg CO_2e L^{-1} of gasoline	At this stage, the result obtained from the sum of the liters of gasoline was based on a main customer of those interviewees who indicated that they made sales outside the locality. The calculation of the annual liters of gasoline was obtained by considering a weekly round trip and asking the interviewee about the amount of gasoline used per trip depending on their vehicle.
				Once the corresponding energy amount has been obtained at this stage, the emission factor for the corresponding type of fossil fuel (gasoline) is multiplied. This will yield the corresponding kilograms of CO_2e per liter of gasoline. (Table 2)
Total emissions from amaranth SASC:				Total sum of carbon dioxide emissions from the stages in the amaranth SASC, expressed in kg CO_2e (I below)

Source: Based on energy emission factors (Instituto Nacional de Ecología y Cambio Climático [INECC], 2014) and information obtained from interviews

4. Results and Discussion

4.1. CO_2 emissions from amaranth SASC in Mexico City

Identifying and analyzing the amount of energy and emissions associated with productive activities can be considered useful for understanding the traceability of LCA and bringing the results closer to a discussion more aligned with sustainability criteria. In this specific case, the interviews conducted with the group of producers provided information regarding the links, and the energy involved in each of them. Table 2 shows the results by LCA chain for amaranth in Mexico City, and the result corresponding to the functional unit [UF] based on 1 kg of popped amaranth.

The first column describes the stages of LCA, while the second indicates the energy inputs, as well as the machinery or activity in which these inputs are used. In the third column, the quantities of each energy source used and the corresponding unit of measurement are shown. The fourth column contains the energy emission factor for conversion to CO_2 terms, and the fifth column displays the final results by production stage and by type of energy. CO_2 emissions are measured in kilograms, and when summed, the total amount of impacts is shown in the sixth column.

The total quantification of the environmental impact generated by the amaranth SASC in Mexico City corresponds to 72,883.06 kg CO_2e. Columns 7 to 9 correspond to the equivalent value of the functional unit; column seven shows the energy carriers in their unit of measure (liters or kilograms), column eight includes the result of multiplying the amount of each energy carrier proportional to the functional unit [*CEPUF*] by the CO_2 emission factor of each energy carrier [cf_i], and column nine sums the CO_2 emissions by stage corresponding to the functional unit, resulting in 1.45 kg CO_2e per kilogram of popped amaranth. The result of the functional unit is detailed in the following sections.

4.2. Stage in primary production: energy and emissions

In principle, the results of the analysis at this stage, through the interviews, show an interesting trend regarding ecological principles in food production by the producers, which is reflected in the fact that, on average, only 1 in 4 of the producers interviewed use agrochemical inputs, while the rest indicated applying organic inputs. In this regard, 20% of the producers reported having maintained their production units free of agrochemicals for between 1 and 7 years, in adherence to agroecological practices. For this purpose, the size of the agricultural production units becomes relevant, as they generally range between 0.5 and 5 hectares, which facilitates management under agroecological principles.

On the other hand, 94% of producers maintain practices based on knowledge and expertise regarding agrobiodiversity, understood as the planting of different crops together with amaranth, which constitute a dynamic space of genetic resources (Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [[CONABIO], 2016), with crops such as corn and beans, among others in trend, like quinoa, and the combination of other activities such as beekeeping.

The proximity between the producers' homes and the farmland creates a local circuit that supports activities associated with the amaranth SASC, reducing CO_2 emissions, particularly those related to crop management, pest control, weed removal, and harvesting—activities that are done on foot and by bicycle, though not by the majority. Table 3 details the CO_2 emissions resulting from the first stage of the SASC per 1 kg of amaranth.

As can be seen, the use of machinery for planting and vehicles for transportation (practices carried out by 78% of the producers) has generated emissions

Table 2. Energy and CO_2e emissions in the CCA of amaranth in Mexico City and the HCO_2 of its functional unit.

Stage	Energy input (i)*	SASC inventory unit of measure (e_i)	Energy emission factor (cf_i).	CO_2 emissions for the SASC	Total CO_2 emissions per stage in the SASC	Amount of energy proportional to the Functional Unit	CO_2 emissions from UF (cfi *CEPUF)	HCO_2 from UF per stage and sum
			kg CO_2e	kg CO_2e	kg CO_2e	(CEPUF)		kg CO_2e
Primary production	Diesel	325 L	2.599	844.68	2,597.79	0.0034 l	0.0089	0.0276
	Gasoline	774 L	2.265	1,753.11		0.0082 l	0.0186	
Harvesting	Diesel	758.8 L	2.599	1,972.12	6,062.71	0.0080 l	0.0209	0.0644
Post-harvesting	Gasoline	1.806 L	2.265	4,090.59		0.0192 l	0.0435	
Processing	LP gas	11,054 kg	3.01	33,272.54	51,934.94	0.0934 kg	0.2813	1.2264
	Coal	6,400 kg	2.916	18,662.40		0.3240 kg	0.9450	
Marketing	Gasoline	5,425 L	2.265	12,287.63	12,287.63	0.0577 l	0.1307	0.1311
Total (I)		-	-		**72,883.06**			**1.45**

Source: Based on information obtained from interviews, energy emission factors (INECC, 2014) and Keoleian & Spitzley (2006) equation.

Note: To demonstrate the traceability of the energy inventory, the average annual consumption of fossil fuels by the producers interviewed corresponds to the following: diesel: 33.85 liters, gasoline: 250.15 liters, LP gas: 345.4 kg, and coal: 200 kg.

Table 3. Energy use and CO_2e emissions in primary amaranth production in Mexico City.

Stage	Energy input (i)	Liters of energy equivalent to that used in the functional unit (measured per kg of amaranth))	Emissions kg CO_2e	Total emissions in kg CO_2e per stage
Primary production	Diesel	0.0035	0.0090	0.0276
	Gasoline and crop management ac-tiv-ities)	0.0082	0.0187	

Table 4. Energy use and CO_2e emissions in the harvesting and post-harvesting of amaranth in Mexico City

Eslabón	Input *(i)* energético	Litros del energético equivalente a lo utilizado en la unidad funcional (medida por kg de amaranto)	Emisiones kg CO_2e	Total de emisiones en kg CO_2e por eslabón
Harvest and post-harvest	Energy	0.008	0.0210	0.0645
	Diesel	0.0192	0.0435	

of 0.0276 kg CO_2e and accounts for 2% of the total emissions of the amaranth SASC.

It is worth mentioning that, in primary production, it was observed that producers used bicycles and walked to the agricultural production units, taking advantage of geographical proximity, as well as the efficient and shared use of agricultural machinery resulting from their organization, which may be contributing to a reduction in GHGs.

4.3. Harvest and post-harvest stage: energy use and emissions

In the harvesting link, the energy inputs are diesel, used in the machinery known as a thresher, which through the mechanical process of crushing the plant quickly extracts the amaranth grain (Secretaria de Pueblos y Barrios Originarios y Comunidades Indígenas Residentes [SEPI], 2017), facilitating the cleaning and obtaining of the tiny seed. Likewise, in the post-harvest stage, transporting the amaranth load to industrial workshops or storage warehouses requires the use of gasoline. As can be seen in Table 4, the result of CO_2 emissions in the harvesting and post-harvest stage together generates 0.0645 kg CO_2e per kg of amaranth, which represents 4% of the total emissions of the amaranth's SASC.

When comparing the emissions in kg CO_2e between primary production and the harvest- and post-harvest stages, it is observed that the latter has higher emissions; The above corresponds to the organization of the activities by the producers in the production units, that is, in the planting, the use of the machinery to make the furrows is shared, exclusively on the days that the machinery is used and used more efficiently by several producers. Likewise, another factor to consider is the agronomic conditions of the territory, since the furrowing machinery cannot be used in all terrains, as is the case in some areas of Xochimilco where production is carried out on steep slopes and, therefore, in some cases, producers must do the furrowing manually and do not use machinery.

Finally, the transfers of producers to production units, in some cases and due to the lack of infrastructure, can be carried out exclusively on foot or by bicycle, where motorized means of transport are not used, which helps reduce the use of fossil fuels.

4.4. Processing stage: energy and emissions

On the other hand, and as the third stage in the amaranth CEC in Mexico City, processing refers first of all to the roasting (or popping) process to which the amaranth seed is subjected and which may involve, on the one hand, artisanal practices that involve the use of rudimentary attachments such as the "comal" that requires coal or, on the other hand, the use of specialized machinery such as stoves that use LPG; this, according to the technological capacity available to the producer. As can be seen in Table 5, the emission result for this stage is 1.2264 kg of CO_2e, which for the functional unit (1 kg of amaranth) is 0.0935 kg of

Table 5. Energy use and CO_2e emissions in amaranth processing in Mexico City.

Stage	Energy input (i)	kg of energy equivalent to that used in the functional unit (measured per kg of amaranth))	Emissions kg CO_2e	Total emissions in kg CO_2e per stage
Transformation	Energy	0.0935	0.2814	1.2264
	LPG	0.3241	0.9451	

Table 6. Energy use and CO_2e emissions in amaranth marketing in Mexico City.

Stage	Energy input (i)	Liters of energy equivalent to that used in the functional unit (measured per kg of amaranth))	Emissions kg CO_2e	Total emissions in kg CO_2e per stage
Marketing	Gasoline	0.0577	0.1307	0.1307

LPG and 0.3241 kg of coal respectively. This represents 85% of the total emissions of the SASC, making it the stage with the highest polluting contribution in the entire chain.

It is worth noting that, after popping, amaranth goes through other processing stages that add value, in what is sometimes known as a second stage of processing to create foods with added ingredients, allowing for a diversified range of products based on amaranth.

4.5. Marketing stage: energy and emissions

In this regard, the analysis of energy consumption at this stage quantified 5,425 liters of gasoline used annually, which is equivalent, in terms of the functional unit, to 0.1307 CO_2e emissions per kg of amaranth, as can be seen in Table 6, and which represents 9% of the SASC pollution from amaranth in Mexico City.

From the interviews, it is worth noting that, at this stage, amaranth producers use various marketing channels, mostly locally (without formal points of sale), and in places such as fairs, local markets, direct sales in offices or educational centers, or even to other resellers or marketers.

The amaranth analyzed in the context of SASC presents a CO_2 emissions result that could be considered environmentally efficient when compared to other food products (as can be seen in Table 7 in the following section). Given this, the factors of both geographical and organizational proximity in the chain structure, as well as the proximity to the peri-urban market, are considered favorable elements in reducing environmental impacts related to CO_2 emissions.

Therefore, the total sums of the results obtained for each stage in the amaranth SASC show that for every kilogram of popped amaranth, 1.45 kg of CO_2e is emitted.

4.6. Comparative analysis of the CO_2e footprint of other foods

Despite the above result, it is worth asking: What does it mean that, in total, the entire amaranth chain per kg of seed generates 1.45 kg of CO_2e? This could be better answered by comparing the CO_2 emissions of other foods that, like amaranth, can be considered sources of protein, such as meat, rice, and even others, such as wine.

Table 7 and Figure 4 show a comparative analysis of the carbon footprint of different foods based on their functional unit. The studies considered used the life cycle methodology, and each bar in the graph shows CO_2 emissions. In Table 7, the first column presents information corresponding to the different stages that make up the value chain (and the rows for stages A to C) depending on the food. The last row of this table shows the total emissions in kg CO_2e corresponding to the functional unit of each food. It should be noted that this comparison of data from different studies was based on the information shown in them, so in some cases it only includes CO_2e emissions without the amounts of energy, and not all stages match the same links due to the diversity of foods analyzed.

The second column shows the energy consumption and emissions in kg CO_2e for the stages corresponding to livestock breeding, processing, and distribution for obtaining organic meat (meat obtained from livestock raised without synthetic elements and fed with organic crops). The third column shows the energy consumption and emissions in kg CO_2e per production stage for one ton of oats, from grain production to transport. The fourth column shows the emissions in kg CO_2e for the stages involved in the production of 750 ml of organic red wine, from grape production to bottling, with the corresponding emissions in kg CO_2e. The fifth column shows the emissions in kg CO_2e for the stages in the production of one ton of greenhouse tomatoes, covering primary production, auxiliary equipment, and waste transportation. The sixth column shows the emissions in kg CO_2e per stage for 1 kg of milled rice, including grain production, harvesting, management, and transportation.

Compared to similar values obtained in CO_2 measurements per kg of functional unit in other food products, we can mention that 1 kg of milled rice releases 1.47 kg of CO_2e and 1 kg of organic meat emits 24.46 kg of CO_2e. Organic red wine corresponding to the functional unit of 750 ml releases 1.29 kg of CO_2e, while for each kg of amaranth, 1.45 kg of CO_2e is released. Figure 4 shows this information, including the case of amaranth, whose values were determined in this study.

In the carbon footprint by stage, we find that in stage A (which may involve the transportation of livestock and activities related to primary production, harvesting, and post-harvesting of grain or grapes) the environmental impact varies greatly, as shown by values ranging from 0.044 kg CO_2e for red wine to 20.98 kg CO_2e for organic meat. Across the five production chains, the primary production of organic meat has the most significant environmental impact derived from cattle breeding and fattening activities. In contrast, red wine is 475 times less polluting in this stage than organic meat.

On the other hand, stage B corresponds to pollutant emissions from activities related to food processing (natural gas used in slaughterhouses, energy in wine cellars, rice milling operations, and LPG or coal for roasting amaranth seeds) and shows emissions below 1.3 kg CO_2e. in this sense, amaranth is the most polluting food at this stage due to the use of coal, which has a lower calorific value than LPG and emits more CO_2.

In stage C, which corresponds to the fuels needed for meat refrigerants, wine bottles, labels, and containers, and the transportation of rice or amaranth, emissions are shown where the highest result, with 1.00 and 0.957 kg CO_2e, belongs to meat and red wine, respectively, This is the most polluting stage in these value chains because it takes into account the energy used to manufacture bottles and labels and the use of refrigerant gas.

These results allow us to reflect on the LCA of amaranth, which, despite requiring initial processing, maintains emissions below 1.45 kg CO_2e per functional unit (kg of amaranth), keeping it within a range of CO_2 emissions consistent with or similar to those reported for milled rice or organic red wine.

It should be noted that, in addition to this environmental impact result due to CO_2 emissions from amaranth, other key factors to consider, which may strengthen the premise of amaranth as a key option for reducing the carbon footprint, lie in its being a high-protein food of plant origin and a pseudocereal (Cano, 2022), Therefore, consumer preference for amaranth could contribute to a decrease in the consumption of animal-based foods, which tend to have a higher carbon footprint (Ramírez-Reyes, 2020). Likewise, the factor of local production and its proximity to the consumer favors a reduction in the number of kilometers traveled to obtain food, compared to imported cereals, such as corn from the United States, which Mexico imports (United States Department of Agriculture [USDA], 2025).

4.7. Sensitivity analysis of the SASC amaranth in Mexico City

On the other hand, in the LCA analysis of amaranth, it is important to determine how changes in the consumption of the main fuels can modify the result of GHG emissions, so that it is necessary to carry out a sensitivity analysis, which evaluates the efficiency of the changes made in input variables on output variables to verify the feasibility of the proposed solution (Pérez-Vega et al., 2020).

Given this perspective, a sensitivity analysis (Table 8) is presented with parameters for reductions and increases in the use of fossil fuels and an example applicable from the integration of technological inno-

Table 7. Comparison of CO_2e footprints of other foods

Stage	**Organic meat**	**Oats**	**Organic red wine**		**Greenhouse tomatoes**	**Ground rice**
Food	(1 kg)	(1 ton)	(750 ml)		(1 ton)	(1 kg)
A *Rearing/primary production*	Transportation in breeding (21,684 L fuel)	Grain production (2.5 L diesel and 8 L propane)	Grape production (mobile fuels)		Greenhouse production (Fertilizer)	Grain production
(kg CO_2e)	20.98	449	0.044		88	1.02
B *Processing/industry*	Slaughterhouse (37,060 kg natural gas)	Cereal production (12.7 L heating oil)	Wine in the cellar (electricity)		Auxiliary equipment	Harvesting and management
(kg CO_2e)	0.27	115	0.020		77	0.0784
C *Distribution/transport/ packaging*	Refrigeration (5.6 refrigerant gas)	Transportation and storage (2.5 L diesel)	Bottles and containers	Tags	Waste transportation	Transportation
(kg CO_2e)	1.00	632	0.946	0.011	3.1	0.0057
Total carbon footprint per functional unit (kg CO_2e)	24.46	1.196	1.29		250	1.47

Source: Based on Brodt et al. (2014); Torrellas et al. (2012); Vitali et al. (2018); Rodrigues Viana et al. (2023); and Petti et al. (2006).

vations for the analysis of options for changes in the use of energy in the production of one kilogram of amaranth in Mexico City.

In this sensitivity analysis, using hypothetical scenarios, we consider reducing or increasing the amounts of energy used to produce the functional unit of amaranth SASC (1.45 kg CO_2e). This is based on the results per stage of fossil fuel energy sources and CO_2 emissions (Table 8, row 3), and numerical scenarios are proposed that show increases in energy use of 10% and a change in the result of 1.59 kg CO_2e, as well as a 10% reduction in energy with an emissions result of 1.30 kg CO_2e (Table 8, row 4) and finally (Table 8, row 5) a 20% reduction in fuels, where 1.16 kg CO2e is emitted according to this scenario. Table 8 is divided into columns: column 1: scenario (increase or reduction), column 2: change (percentages applied), columns 3, 4, 5, and 6, the production stages (primary production, harvest-post-harvest, processing, marketing), and column 7 shows the environmental impact in kg CO_2e for each scenario proposed.

This hypothetical source of energy increases and decreases allowed us to establish the possibilities for reducing kg CO_2e per functional unit for different scenarios, where a 20% reduction in emissions could reduce the carbon footprint per kilogram of amaranth by up to 1.15 kg CO_2e. However, there is a need to consider the direct integration of technological innovations in combination with fossil fuels within the stages of the amaranth SASC to improve energy efficiency and, consequently, reduce CO_2 emissions. Below, we show the integration of technological innovations in the form of proposals that bring us closer to the results of the reduction scenarios proposed in Table 8.

4.8. Technological innovations for reducing CO_2 emissions in amaranth SASC

Through government programs, the Secretaria de Agricultura, Ganadería, Desarrollo Rural, Pesca y Alimentación (SAGARPA, now SADER) has promoted the use of technologies that take advantage of renewable energy sources in the agricultural sector in Mexico, such as the implementation of solar thermal and photovoltaic systems (Secretaria de Energía y Comisión Nacional para el Uso Eficiente de la Ener-

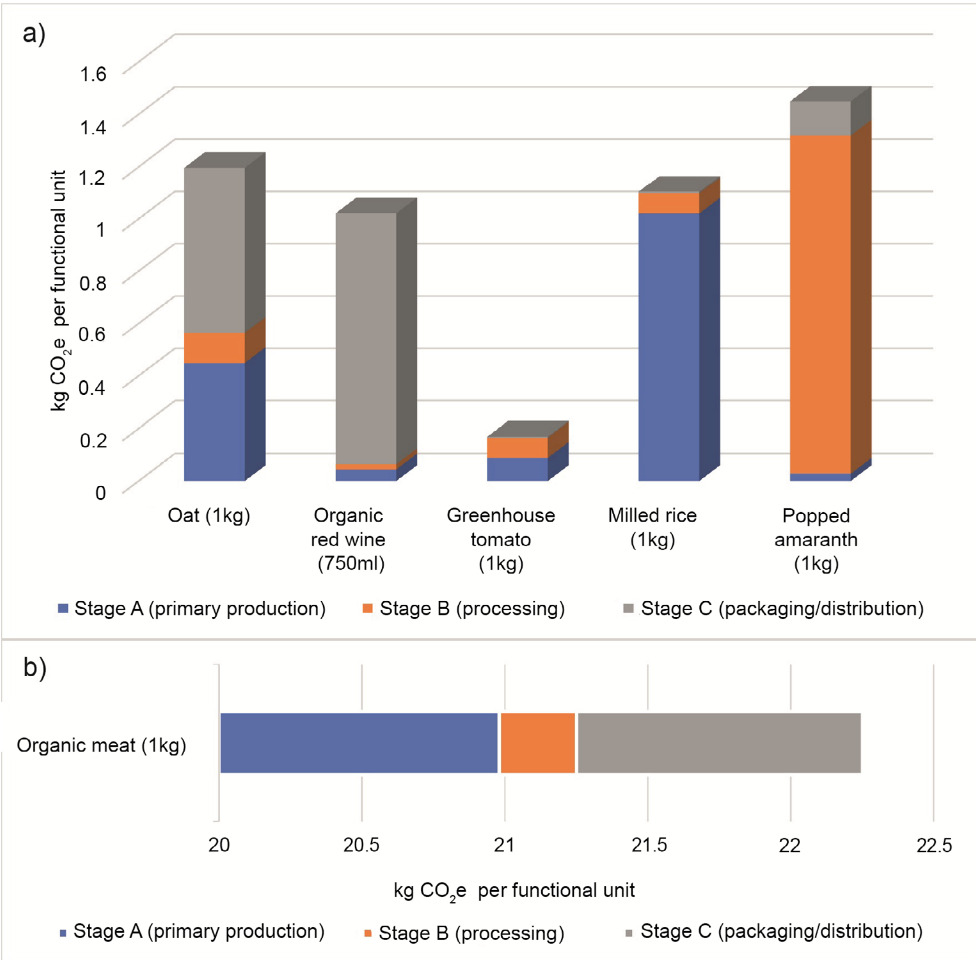

Figure 4. Comparative carbon footprint by agri-food chain stage: a) Oats, organic red wine, greenhouse tomatoes, milled rice, and popped amaranth; b) Organic meat

gía [SENER] and Comisión Nacional para el Uso Eficiente de la Energía [CONUEE], 2025) which, in the case of the amaranth SASC, the integration of these technologies has been proposed from the amaranth product system with a view to achieving sustainable production processes in the value chain, through the installation of solar panels for amaranth cracking machines (SEPI, 2017), which could contribute to reducing CO_2 emissions from the processing stage.

Likewise, the technology-based innovations applied in amaranth popping machines are those of Argumedo-Macías (2021), an innovation that optimizes seed quality and increases popping capacity per hour, reducing energy consumption by completing the process in less time than other machines, such as LPG-based popping machines. Another option proposed for small producers who do not have a roasting machine and use LPG stoves is induction stoves, which have the advantage of directly and quickly heating the container used to roast the seed and offering greater heat output. These stoves use electricity to operate (Orialnitak, 2025). The proposal to reduce emissions in amaranth SASC refers to the replacement of LPG stoves in the processing stage with induction stoves. This replacement, in addition to electromobility, could provide a reduction of up to 33% in CO_2e emissions compared to the baseline scenario in Table 8, while maintaining the same amaranth production.

It is also worth noting that trends in the use of electric mobility have increased rapidly throughout the country, which is why the incorporation of electric or hybrid vehicles for private use or in public transport is being promoted to reduce CO_2 emissions from the use of fossil fuels (Centro Nacional de Control de la Energía [CENACE], 2024). In the case of amaranth SASC, this could mean modernizing commonly used vehicles, thereby reducing the carbon footprint of trips to agricultural production units, crop transportation, and distribution during the amaranth marketing stage. In this regard, it is estimated that electric vehicles require only 38.5% of the electrical energy used by an internal combustion vehicle to travel the same distance (CENACE, 2024). On the other hand, the scenario of increased CO_2 emissions can be represented under the assumption that the vehicle fleet used to transport the product in the three stages is aging, as is the harvesting equipment, combined with minimal maintenance and low efficiency, this leads to higher fuel consumption to cover the same distances and harvest the same amount of amaranth. This results in an approximate 9% increase in CO_2 emissions compared to the current scenario.

This sensitivity analysis identified areas of opportunity to improve pollutant emission reductions through the use or application of technological innovations, specifically in activities with the greatest environmental impact in amaranth SASC. Although there are no programs in Mexico City exclusively focused on encouraging energy innovation with a focus on peri-urban agri-food production, multi-chain amaranth producers benefit indirectly from specific public policies and programs that prioritize food self-sufficiency and sustainability, such as the 2020-2024 Sectoral Program for Agriculture and Rural Development (SADER, 2020b). At the local level, territorial governance in Mexico City is embodied in the General Land Use Plan for Mexico City, (Instituto de Planeación Democrática y Prospectiva de la Ciudad de México, 2023), which promotes the protection and valuation of conservation land, where most peri-urban agri-food production is located. Likewise, the sustainable production approach can open the door for producers to access programs or financing for the acquisition of machinery that emits fewer pollutants. Given these results and discussions, it is worth noting that contemporary food challenges, which are prevalent in the globalized agri-food system, can find solutions in local agricultural chains and practices, as well as in traditional crops, leading to models that promote sustainability in agri-food matters. The role of amaranth in the analysis of the peri-urban agri-food system in Mexico City is, therefore, relevant because it allows us to reveal and even empirically contrast theoretical premises, sometimes ossified, around SASCs, since, while recognizing the ability of this crop to contribute favorably to the food issue in areas such as Mexico City (due to its nutritional qualities, its resilience as an agricultural crop, and its sociocultural impact), it also allows for a critical analysis of this dynamic, identifying strengths as well as areas for action and improvement.

5. Conclusions

Although SASCs have been assumed to be more sustainable, this study demonstrates the need to reflect on the various aspects that comprise them. The analysis of the different stages in the chain, energy consumption, production processes, type of food, place of origin and processing, proximity to the market, among others, are factors that can be strategic in addressing prevalent problems such as environmental impacts and their effects on climate change.

In this regard, it was found that although the proximity of peri-urban production and marketing areas can help reduce GHG emissions in this chain, the processing stage (which is the stage with the highest

CO_2 emissions) requires the implementation of more sustainable and innovative processing techniques that allow for better use of fuels or the introduction of methods based on renewable energies. Otherwise, the potential benefits of SASCs could be overshadowed by the negative effects of GHGs.

Following this logic, it was found that there is an opportunity in the LCA of amaranth to introduce innovations that reduce its GHG emissions. Regarding the processing stage, which has the greatest environmental impact in Mexico City, since coal is a less efficient fuel than others, such as LPG or electricity, and contributes to increasing the carbon footprint of this food, it was identified that the integration of induction stoves that run on electricity could reduce CO_2 emissions by up to 13% in this process alone. In addition to the above proposal, the study suggests reducing CO_2 emissions in all stages by replacing vehicles that currently run on gasoline with electric vehicles, which would constitute a 20% reduction in CO_2 emissions for this study, achieving a total reduction of 33% in amaranth LCA emissions with the same level of production. This study proposes the integration of technological innovations that are already in place to improve the energy efficiency of production processes, while effectively generating innovations adapted to amaranth production in the peri-urban context.

On the other hand, it is worth mentioning that this study agrees with Majewski et al. (2020) in that the sustainability of SASCs is not an intrinsic element due to their local nature or proximity to the peri-urban market, since the diversity of projects and practices that exist and will continue to emerge in peri-urban areas, and which could constitute short chains, require a specific analysis to identify and improve environmental impacts in order to benefit the environment. Likewise, and as mentioned previously, when comparing GHG emissions in other foods, such as meat, the value obtained from amaranth stands out (1.45 kg CO_2e per kg of amaranth versus 24.46 kg CO_2e per kilogram of organic meat) This positions it as a sustainable option not only environmentally, but also because amaranth is a high-protein food that could contribute to replacing meat protein consumption in peri-urban diets.

It is also worth mentioning that one of the limitations encountered during the research arose during stage two, which involved obtaining data for inventory analysis. Although amaranth producers were consulted directly about this information, the information provided by the interviewees was sometimes ambiguous, especially with regard to the marketing stage, due to the multiple transfers that these actors carry out. However, we believe that these challenges could be overcome with approximations of the data. Another limitation of the study was the lack of information regarding agricultural inputs, especially agrochemicals, possibly used in planting, since the refusal of producers to use these inputs led the research to eliminate them as a component of the analysis.

In this vein, one area of opportunity for further study or research is the need to include information on other inputs used in amaranth SASC in order to broaden the analysis of the amaranth life cycle, i.e., to identify other resources used in the value chain (seeds, fertilizers, water, electricity, packaging) to increase the scope of the study. It would also be relevant to include other analytical categories such as land use, precipitation, or other energy components as climate change variables. Similarly, it would be very relevant to gather more information on the social and economic contexts of amaranth producers to understand the entire chain more holistically.

Table 8. Sensitivity analysis of amaranth SASC in Mexico City

Scenario	Change	Primary		Post-harvest		Processing		Marketing	Environmental impact
		Diesel	Gasoline	Gasoline	Diesel	LPG	Coal	Gasoline	Emissions
	%	L	L	L	L	kg	kg	L	kg CO_2e
10% increase	10	0.00380	0.00906	0.02113	0.00888	0.10283	0.35651	0.06348	*1.59*
Base	0	0.00346	0.00823	0.01921	0.00807	0.09348	0.32410	0.05771	1.45
10% reduction	-10	0.00311	0.00741	0.01729	0.00727	0.08413	0.29169	0.05194	*1.30*
20% reduction	-20	0.00277	0.00659	0.01537	0.00646	0.07478	0.25928	0.04617	*1.16*

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Contributor roles

- María del Pilar Ortiz Martínez: conceptualization, formal analysis, investigation, software, validation, visualization, writing—original draft; writing—review & editing.
- Laura Elena Martínez Salvador: conceptualization, formal analysis, validation, visualization, writing—original draft; writing—review & editing.

Data availability

The authors have not been granted permission to share the data.

Artificial Intelligence Use Statement

The authors declare that no artificial intelligence has been used in the preparation of the manuscript.

Ethical implications

The authors state that semi-structured interviews were conducted in this research. All participants were informed of the objectives of the research, and were asked verbally about their voluntary participation. Likewise, to protect personal data, the document does not present or publish any personal data of the interviewees. Similarly, the research was conducted in accordance with the "Principles and values that guide the behavior of university students," issued in the Code of Ethics of the Universidad Nacional Autónoma de México.

Conflict of interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

References

Argumedo-Macías, A. (2021). Reventadora de semilla de amaranto (*Amaranthus* sp.). *Agro-Divulgación*, *1*(0), 85-86. https://doi.org/10.54767/ad.v1i1.24

Aubry, C., & Kebir, L. (2013). Shortening food supply chains: A means for maintaining agriculture close to urban areas? The case of the French metropolitan area of Paris. *Food Policy*, *41*, 85–93. https://doi.org/10.1016/j.foodpol.2013.04.006

Avila-Sanchez, H. (2024). Producción y consumo alimentario en espacios periurbanos de proximidad. Procesos socio-territoriales en la conformación de los sistemas agroalimentarios. *Investigaciones Geográficas*, *113*, e60806. https://doi.org/10.14350/rig.60806

Azapagic, A., & Clift, R. (1999). Life cycle assessment and multiobjective optimisation. *Journal of Cleaner Production*, *7*(2), 135–143. https://doi.org/10.1016/S0959-6526(98)00051-1

Benis, K., & Ferrão, P. (2017). Potential mitigation of the environmental impacts of food systems through urban and peri-urban agriculture (UPA) – a life cycle assessment approach. *Journal of Cleaner Production*, *140*, 784–795. https://doi.org/10.1016/j.jclepro.2016.05.176

Brodt, S., Kendall, A., Mohammadi, Y., Arslan, A., Yuan, J., Lee, I.-S., & Linquist, B. (2014). Life cycle greenhouse gas emissions in California rice production. *Field Crops Research*, *169*, 89–98. https://doi.org/10.1016/j.fcr.2014.09.007

Canfora, I. (2016). Is the Short Food Supply Chain an Efficient Solution for Sustainability in Food Market? *Agriculture and Agricultural Science Procedia*, *8*, 402–407. https://doi.org/10.1016/j.aaspro.2016.02.036

Cano, E., (2022). *Valor nutricional y biológico del amaranto variedad Amaranthus Caudatus L. (kiwicha).* Universidad Yécnica de Ambato. https://repositorio.uta.edu.ec/handle/123456789/34924

Centro Nacional de Control de la Energía, [CENACE]. (2024). *Programas de ampliación y modernización de la red de transmisión y de los elementos de las redes generales de distribución que corresponden al mercado eléctrico mayorista. PAMRNT 2024 – 2038.* https://www.cenace.gob.mx/Docs/10_PLANEACION/ProgramasAyM/Programa%20de%20Ampliaci%C3%B3n%20y%20Modernizaci%C3%B3n%20de%20la%20RNT%20y%20RGD%202024%20%E2%80%93%202038.pdf

Chiffoleau, Y., Millet-Amrani, S., Rossi, A., Rivera-Ferre, M. G., & Merino, P. L. (2019). The participatory construction of new economic models in short food supply chains. *Journal of Rural Studies*, *68*, 182–190. https://doi.org/10.1016/j.jrurstud.2019.01.019

Comisión Económica para América Latina y el Caribe [CEPAL], Organización de las Naciones Unidas para la Alimentación y la Agricultura [FAO], & Instituto Interamericano de Cooperación para la Agricultura [IICA]. (2014). *Fomento de circuitos cortos como alternativa para la promoción de la agricultura familiar. Perspectivas de la Agricultura y del Desarrollo Rural en las Américas: una mirada hacia América Latina y el Caribe*. Boletín CEPAL/FAO/IICA. https://hdl.handle.net/11362/37152

Comisión Nacional para el Conocimiento y Uso de la Biodiversidad [CONABIO]. (2016). *La milpa*. CONABIO. https://www.biodiversidad.gob.mx/diversidad/sistemas-productivos/milpa

Cucurachi, S., Scherer, L., Guinée, J., & Tukker, A. (2019). Life Cycle Assessment of Food Systems. *One Earth*, *1*(3), 292–297. https://doi.org/10.1016/j.oneear.2019.10.014

Cui, Y., Diarrassouba, I., Joncour, C., & Michel Loyal, S. (2024). Optimization and analysis of the impact of food hub location on GHG emissions in a short food supply chain. *Sustainability*, *16*(17), 7781. https://doi.org/10.3390/su16177781

Del Rosario, P., Palumbo, E., & Traverso, M. (2021). Environmental product declarations as data source for the environmental assessment of buildings in the context of level(s) and DGNB: How feasible is their adoption? *Sustainability*, *13*(11), 6143. https://doi.org/10.3390/su13116143

Dieleman, H. (2017). Urban agriculture in Mexico City; balancing between ecological, economic, social and symbolic value. *Journal of Cleaner Production, 163* (Supplement), S156-S163. https://doi.org/10.1016/j.jclepro.2016.01.082

Folinas, D., Aidonis, D., Triantafillou, D., & Malindretos, G. (2013). Exploring the greening of the food supply chain with lean thinking techniques. *Procedia Technology*, *8* (Supplement), S416–S424. https://doi.org/10.1016/j.protcy.2013.11.054

Iglesias, H. (2005). Relevamiento exploratorio del análisis del ciclo de vida de productos y su aplicación en el sistema agroalimentario. *Contribuciones a la Economía, 2*(1) https://contribucionesalaeconomia.com/index.php/contribuciones-economia/article/view/591

Instituto de Planeación Democrática y Prospectiva de la Ciudad de México. (2023). *Programa General de Ordenamiento Territorial de la Ciudad de México*. IPDP. https://www.ipdp.cdmx.gob.mx/storage/app/uploads/public/648/282/400/648282400131720032 7314.pdf

Instituto Nacional de Ecología y Cambio Climático [INECC]. (2014). *Factores de emisión para los diferentes tipos de combustibles fósiles y alternativos que consumen en México.* Informe técnico No.3. INECC. https://www.gob.mx/inecc/documentos/factores-de-emision-para-los-diferentes-tipos-de-combustible-fosiles-que-se-consumen-en-mexico

International Standard ISO 14040:2006. Environmental management — Life cycle assessment — Principles and framework. https://www.iso.org/obp/ui#iso:std:iso:14040:ed-2:v1:en

International Standard ISO 14064-1:2018. Greenhouse gases — Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals. https://www.iso.org/obp/ui#iso:std:iso:14064:-1:ed-2:v1:en

Jarzębowski, S., Bourlakis, M., & Bezat-Jarzębowska, A. (2020). Short Food Supply Chains [SFSC] as Local and Sustainable Systems. *Sustainability*, *12*(11), 4715. https://doi.org/10.3390/su12114715

Jujnovsky, J., Ramos, A., González Gómez, R., Hudler Schimpf, C., Cetina Arenas, L., Ortiz Vázquez, R., & Almeida-Leñero, L. (2022). Herramientas para evaluar servicios ambientales en el suelo de conservación de la Ciudad de México. *Sociedad y Ambiente*, (25), 1–26. https://doi.org/10.31840/sya.vi25.2512

Keoleian, G. A., & Spitzley, D. v. (2006). Chapter 7 Life cycle based sustainability metrics. In M. A. Abraham (ed.), *Sustainability Science and Engineering, 1,* (pp. 127–159). Elsevier. https://doi.org/10.1016/S1871-2711(06)80014-0

Lang, T., & Irving, J. (2006). Locale / globale (food miles)'. *Slow Food*. 94-97. https://www.citystgeorges.ac.uk/__data/assets/pdf_file/0007/167893/Slow-Food-fd-miles-final-16-02-06.pdf

López-Cruz, I. L., Salazar-Moreno, R., Rojano-Aguilar, A., & Ruiz-García, A. (2012). Análisis de sensibilidad global de un modelo de lechugas (*Lactuca sativa L.*) cultivadas en invernadero. *Agrociencia, 46*(4), 383-397. https://www.agrociencia-colpos.org/index.php/agrociencia/article/view/962

Majewski, E., Komerska, A., Kwiatkowski, J., Malak-Rawlikowska, A., Wąs, A., Sulewski, P., Gołaś, M., Pogodzińska, K., Lecoeur, J.-L., Tocco, B., Török, Á., Donati, M., & Vittersø, G. (2020). Are Short food supply chains more environmentally sustainable than long chains? A Life Cycle Assessment (LCA) of the eco-efficiency of food chains in selected EU countries. *Energies*, *13*(18), 4853. https://doi.org/10.3390/en13184853

Mapes, E. (2015). El amaranto. *Revista Ciencia*, *66*(3), 8-15. https://www.revistaciencia.amc.edu.mx/index.php/vol-66-numero-3/604-el-amaranto

Martínez Salvador, L. E., De Jesús Contreras, D., & Guerrero Jacinto, M. I. (2022). Gobernanza territorial en los procesos de patrimonialización de bienes alimentarios. La "alegría" de amaranto en la Ciudad de México. In L. B. Montes de Oca Barrera, & L. E. Martínez Salvador (eds.), *Caminos de la gobernanza en México. Avances, pausas, obstáculos y retrocesos* (pp. 99–126). Instituto de Investigaciones Sociales, UNAM. https://www.iis.unam.mx/caminos-de-la-gobernanza-en-mexico-avances-pausas-obstaculos-y-retrocesos/

Martínez Salvador, L. E., Hernández, L. G., & Alvarado Ramírez, D. (2021). Cadenas Cortas de Comercialización y seguridad alimentaria: el caso de El Mercado el 100. *Problemas Del Desarrollo. Revista Latinoamericana de Economía*, *52*(206), 197-220. https://doi.org/10.22201/iiec.20078951e.2021.206.69732

Moran Bañuelos, S. H., Soriano Robles, R., & Ramírez Romero, G. (2014). Diversidad biológica en el agroecosistema periurbano del amaranto en el Distrito Federal, México. In E. Guzmán Gómez, G. Espinosa Damián, & R. Diego Quintana (eds.), *Alternativas y transformaciones en el manejo de recursos naturales* (pp. 41-61). Asociación Mexicana de Estudios Rurales, [AMER]. https://agua.org.mx/biblioteca/alternativas-y-transformaciones-en-el-manejo-de-recursos-naturales-volumen-iii-hacia-la-identificacion-de-la-gobernanza-local-del-agua-en-localidades-indigenas-de-la-sierra-nororiental-de-puebla/

Mundler, P., & Rumpus, L. (2012). La route des paniers: réflexions sur l'efficacité énergétique d'une forme de distribution alimentaire en circuits courts. *Cahiers de Géographie Du Québec*, *56*(157), 9-264. https://doi.org/10.7202/1012220ar

Muñoz Torres, M. J., Fernández-Izquierdo, M. Á., Ferrero-Ferrero, I., Escrig-Olmedo, E., & Rivera-Lirio, J. M. (2022). Transitioning the agri-food system. Does closeness mean sustainability? how production and shipping strategies impact socially and environmentally. Comparing Spain, South Africa and U.S. citrus fruit productions. *Agroecology and Sustainable Food Systems*, *46*(4), 540–577. https://doi.org/10.1080/21683565.2022.2039835

Organización de las Naciones Unidas para la Alimentación y la Agricultura [FAO]. (2016). *Memoria del Taller de intercambio de experiencias en cadenas cortas agroalimentarias*. FAO. https://www.fao.org/documents/card/en?details=ff430a91-5825-4499-bcf4-66d8a0d62cc6/

Organización de las Naciones Unidas para la Alimentación y la Agricultura [FAO]. (2017). *Guía para el desarrollo de mercados de productores*. Proyecto "Creación de cadenas cortas agroalimentarias en la Ciudad de México". FAO. https://openknowledge.fao.org/handle/20.500.14283/i8096es

Orialnitak (2025). *Estufas de inducción: ¿Ahorro real de energía?* https://orialnitak.es/consumo-estufa-de-induccion/

Padilla, R., & Oddone, N. (2014). *Manual para el fortalecimiento de la cadena de valor*. Fondo Internacional para el Desarrollo Agrícola [FIDA], y Comisión Económica para

América Latina y el Caribe [CEPAL]. https://repositorio.cepal.org/handle/11362/40662

Pérez-Vega, A., Regil García, H. H., & Mas Caussel, J. F. (2020). Degradación ambiental por procesos de cambios de uso y cubierta del suelo desde una perspectiva espacial en el estado de Guanajuato, México. *Investigaciones Geográficas*, *103*, e60150. https://doi.org/10.14350/rig.60150

Petti, L., Raggi, A., De Camillis, C., Matteucci, P., Sára, B., & Pagliuca, G. (2006). Life cycle approach in an organic wine-making firm: an Italian case-study. In *Fifth Australian Conference on Life Cycle Assessment "Achieving Business Benefits from Managing Life Cycle Impacts"*. Australian Life Cycle Assessment Society. Melbourne. https://ricerca.unich.it/handle/11564/130384

Ramírez Reyes, C. (2020). *Sustitución de proteína animal en albóndigas a partir de harina de amaranto, lentejas y algas nori*. Universidad de los Andes. http://hdl.handle.net/1992/48897

Renting, H., Schermer, M., & Rossi, A. (2012). Building food democracy: Exploring civic food networks and newly emerging forms of food citizenship. *The International Journal of Sociology of Agriculture and Food, 19*(3), 289–307. https://doi.org/10.48416/ijsaf.v19i3.206

Rodrigues Viana, L., Dessureault, P.-L., Marty, C., Boucher, J.-F., & Paré, M. C. (2023). Life cycle assessment of oat flake production with two end-of-life options for agro-industrial residue management. *Sustainability*, *15*(6), 5124. https://doi.org/10.3390/su15065124

Rodríguez-Fernández, Y., Abreu-Ledón, R. & Franz, M. (2019). Mapeo del Flujo de Valor para el análisis de sostenibilidad en cadenas de suministro agroalimentarias. *Ingeniería Industrial*, *40*(3), 316-328. http://scielo.sld.cu/scielo.php?script=sci_abstract&pid=S1815-59362019000300316

Romero-López, A. R., & Ramos, F. M. (2017). Understanding the linkages between small-scale producers and consumers through the analysis of short food supply chains in a local market in Nopala de villagrán, Hidalgo, Mexico. *Cuadernos de Desarrollo Rural*, *14*(79), 1- 16. https://doi.org/10.11144/Javeriana.cdr14-79.ulsp

Salomone, R., & Ioppolo, G. (2012). Environmental impacts of olive oil production: A Life Cycle Assessment case study in the province of Messina (Sicily). *Journal of Cleaner Production*, *28*, 88–100. https://doi.org/10.1016/j.jclepro.2011.10.004

Secretaría de Agricultura y Desarrollo Rural [SADER]. (2020a). *Amaranto, un cultivo ancestral y de alto valor nutricional*. https://www.gob.mx/agricultura/articulos/amaranto-un-cultivo-ancestral-y-de-alto-valor-nutricional?idiom=es

Secretaría de Agricultura y Desarrollo Rural [SADER]. (2020b). *Programa Sectorial de Agricultura y Desarrollo Rural 2020-2024 (SADER-NIS-0507)*. Normateca SADER. https://normateca.agricultura.gob.mx/programa-sectorial-de-agricultura-y-desarrollo-rural-2020-2024-sader-nis-0507

Secretaria de Energía y Comisión Nacional para el Uso Eficiente de la Energía [SENER], & Comisión Nacional para el Uso Eficiente de la Energía [CONUEE]. (2025). *Iniciativas para el aprovechamiento térmico solar y de la eficiencia energética en el sector servicios. Balance 2007 – 2023*. SENER y CONUEE. https://www.gob.mx/cms/uploads/attachment/file/993226/IATSEESS.pdf

Secretaria de Pueblos y Barrios Originarios y Comunidades Indígenas Residentes [SEPI]. (2017). *Con equipo y herramientas Sederec contribuye al ciclo productivo del amaranto*. https://www.sepi.cdmx.gob.mx/comunicacion/nota/con-equipo-y-herramientas-sederec-contribuye-al-ciclo-productivo-del-amaranto

Sistema de Información Agroalimentaria de Consulta [SIACON]. (2023). *Reporte. Módulo Agrícola. SADER y SIAP*. https://www.gob.mx/agricultura/dgsiap/prensa/sistema-de-informacion-agroalimentaria-de-consulta-siacon?idiom=es

Tolentino Martínez, J., & Martínez Salvador, L. (2021). Gobernanza y arreglos institucionales para la revalorización de cultivos agroalimentarios: el caso del amaranto en la región centro en México. In G. Torres Salcido, & R. M. Larroa Torres, (coord.), *Gobernanza y desarrollo territorial. Sistemas agroalimentarios localizados. Análisis y políticas públicas.* (pp. 221-254.) CIALC- UNAM. https://librosoa.unam.mx/handle/123456789/3424

Torrellas, M., Antón, A., López, J. C., Baeza, E. J., Pérez Parra, J., Muñoz, P., & Montero, J. I. (2012). LCA of a tomato crop in a multi-tunnel greenhouse in Almeria. *The International Journal of Life Cycle Assessment, 17*(7), 863-875. https://doi.org/10.1007/s11367-012-0409-8

Torres Salcido, G. (2022). Gobernanza territorial y anclaje de los alimentos. Los Sistemas Agroalimentarios Localizados (Sial). In L. B. Montes de Oca Barrera, & L. E. Martínez Salvador (eds.), *Caminos de la gobernanza en México. Avances, pausas, obstáculos y retrocesos* (pp. 127–158). Instituto de Investigaciones Sociales, UNAM. https://www.iis.unam.mx/caminos-de-la-gobernanza-en-mexico-avances-pausas-obstaculos-y-retrocesos/

United States Department of Agriculture [USDA]. (2025). *Corn and other feed grains - Feed grains sector at a glance*. https://www.ers.usda.gov/topics/crops/corn-and-other-feed-grains/feed-grains-sector-at-a-glance

Vitali, A., Grossi, G., Martino, G., Bernabucci, U., Nardone, A., & Lacetera, N. (2018). Carbon footprint of organic beef meat from farm to fork: a case study of short supply chain. *Journal of the Science of Food and Agriculture*, *98*(14), 5518–5524. https://doi.org/10.1002/jsfa.9098