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An overview of the interactions between food production and climate change

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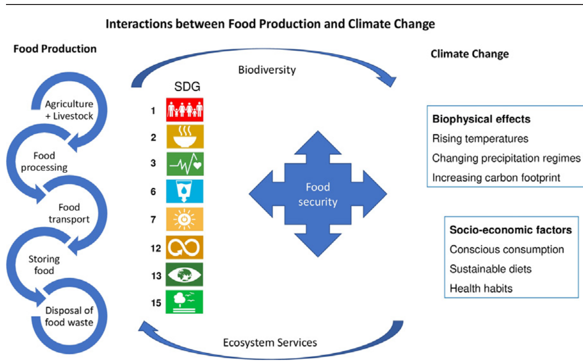
HIGHLIGHTS

- More focus is put on the impact of food production on climate change then v.v.
- Impact of climate change is mostly analyzed in the agricultural stage.
- Different actors in the food supply chain have different impacts on climate change.
- Mitigation strategies for combating climate change are generic, not food oriented.
- Climate change perspective of food production outlines linkage with 8 UN SDGs.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper provides an overview of how food production influences climate change and also illustrates the impact of climate change on food production. To perform such an overview, the (inter)link between different parts of the food supply chain continuum (agriculture production, livestock farming, food processing, food transport and storing, retail food, and disposal of food waste) and climate change has been investigated through a bibliometric analysis. Besides UN Sustainable Development Goal (SDG) 13, associated with climate change, other SDGs that are associated with this overview are goals #1, #2, #3, #6, #7, #12, and #15. Based on the evidence gathered, the paper provides some recommendations that may assist in efforts to reduce the climate-related impacts of food production.

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Contents

1. Introduction

An enormous body of evidence points to the fact that there will be a continuous change in global climatic conditions. Human activities including agriculture were found to be some of the causes (IPCC, 2013; IPCC, 2014; IPCC, 2019; Rosenzweig et al., 2020; Ali and Mujeeb-Kazi, 2021). Several agricultural activities massively contribute to the emission of greenhouse gases (GHG) such as carbon dioxide, methane, and nitrous oxide, which are the main culprits in climate change (Etim et al., 2013; Panchasara et al., 2021). These gases trap the heat from the sun, thereby making the atmosphere warmer—hence the name "greenhouse." (IPCC, 2007; IPCC, 2019). About 21 % of the anthropogenic CO_2 emissions derive from agriculture, forestry, and other forms of land use (NATURECropped, 2022). Approximately 40 % of the planet's surface is used for food production (Crist et al., 2017). This leads to intensive use of soils and soil resources, but also significant water use and impacts on nitrogen cycles and biodiversity (Foley et al., 2011). It also influences climate change. Nonetheless, there is still a need to continually intensify food production to meet the requirements of the growing global population (UN, 2019). This highlights the complexity that exists between human population and agricultural production (Mekuria, 2017; IPCC, 2019; Ali and Mujeeb-Kazi, 2021), especially when considering the impact of the latter on climate change (Ayyildiz and Erdal, 2021).

As reported by the Food and Agriculture Organization (FAO) (2009) and the United Nations (UN) (2017), the global population will increase by over a third (or 2.3 billion people) between 2009 and 2050. Almost all of this growth is projected to take place in the developing countries, and it was also predicted that sub-Saharan Africa's population would witness the highest population growth and central Europe, Eastern Europe, East Asia, and the Asia Pacific the lowest (Ezeh et al., 2020). Analysts have reached a consensus that the current trends indicating significantly faster growth in developing countries than in developed countries will likely remain the same in the future (UN, 2019). Studies posited that food production per capita has increased in several countries of the world due to the green revolution and agricultural intensification, despite rapid population growth (Pellegrini and Fernández, 2018; Wolfgram and Aguirre, 2005). But the report by Tulchinsky and Varavikova (2014) indicated that while most parts of the world have experienced increases in food production, that of sub-Saharan Africa has steadily declined. The same applies to crop yields, which are experiencing reductions (Ray et al., 2012).

It was further observed that developing countries have limited capacity to produce food more quickly than the rate of population growth (FAO, 2017). On the other hand, although developed countries have only one-quarter of the world's population, they produce more than half of the world's food supply (Tulchinsky and Varavikova, 2014). Food production is dominated by them, even though they have a low population growth rate, and unfortunately, several developing countries even lack the hard currency to purchase surplus food from developed countries (Tulchinsky and Varavikova, 2014). Also, obesity, undernutrition, and environmental degradation related to food production coexist in all regions of the world and threaten the food security of most of the population (Swinburn et al., 2019; Bodirsky et al., 2020). It also should be stated that there is a huge yield gaps in many developing countries. By closing these yield gaps, these countries could produce more food quickly than the rate of population growth (Pradhan et al., 2015).

These trends demonstrated that food demand (as shown in the market) will experience continuous growth. The need for cereals (for both food and animal feed use) was forecasted at about 3 billion tonnes by 2050 (Saha, 2017), a rise from about 2.1 billion at present. The advent of biofuels has caused variation in parts of the predicted trends and caused a rise in global demand, based on prices of energy and policies of the government (Malins, 2017). The need for other food products with the capacity to respond to higher incomes in developing countries (such as livestock products, vegetable oils) will be greater than the need for cereals (OECD/FAO, 2020). Feeding a global population of 9.1 billion people in 2050 would call for an increase in overall food production by about 70 % from 2005/07 to 2050 (nearly 100 % in the developing countries) (Askew, 2017). This points to significant rises in several key commodities production. For instance, annual cereal production will have to rise by about a billion tonnes and meat production by over 200 million tonnes to attain a total of 470 million tonnes in 2050, an increase from the current 58 % to 72 % in developing countries (FAO, 2009). Projected food demand is based on current patterns.

With all of the projected rises in food production in the future, there is the need to deploy a sustainable food system to produce enough food to meet the growing population's needs (Bodirsky et al., 2020), while simultaneously mitigating the negative impacts of food production on climate change (Rockström et al., 2016), as food production has been found to influence climate change in various ways (Ritchie and Roser, 2020).

Numerous activities and products within the food production and distribution chain/food system activities (Berners-Lee and Clark, 2019) - including producing food, transporting it, and storing wasted food in landfills (Gerber et al., 2013) - have been found to generate different degrees of associated greenhouse gases (GHG). These emissions are called "carbon footprints" with the rule of thumb that "the bigger the carbon footprint, the bigger the contribution to climate change." (Nowadays, the term "carbon footprint" is used for all the climate change-causing greenhouse gases, not just carbon dioxide or other carbon derivatives). Of these sources, livestock production contributes the largest carbon footprint (Ayyildiz and Erdal, 2021). GHG emissions from food system account for 35 % of global total anthropogenic GHG emissions of which 57 % corresponds to the production of animal-based food (including livestock feed) (Xu et al., 2021). According to the IPCC WG III report released in April 2022 (NATURECropped, 2022), the agriculture, forestry and land-use sector (AFOLU) accounted for up to 21 % of global total anthropogenic GHG emissions in the period 2010–2019. The global food system, e.g., production, processing, and distribution, accounts for about one third (23–42 %) of global GHG emissions. Regarding the supply chain, which accounts for 18 % of food emissions, the food transport contributes to only 6 % of the total emissions (Poore and Nemecek, 2018; World Data, 2019). Meat production from ruminant animals, such as cattle and goats, are particularly emissions-intensive (Tilman and Clark, 2014). Activities such as manure treatment, utilization of farm equipment and synthetic fertilizer application also have carbon footprints (Jaiswal and Agrawal, 2020). Overall, the methane (CH4) associated with livestock production, the nitrous oxide (N2O) generated from application of synthetic fertilizer, and carbon dioxide from both the burning of fossil fuels and grassland/deforestation influence climate change (NASA, 2018). Besides primary production, contribution of other actors in the food chain to climate change have also been analyzed such as processing of dairy and meat products (Djekic et al., 2014; Djekic and Tomasevic, 2016), maintain the cold chain (Coulomb, 2008) or food preparation and cooking (Xu et al., 2015).

Despite a large number of papers mainly covering the impact of food production on climate change, it still stays unclear how to combat this challenge on a global scale (Smith and Gregory, 2013; Ritchie and Roser, 2020). Therefore, this study aimed to analyze publications associated with climate change and food production from farms to consumers (and back). The working hypotheses that are used in designing this study were: (1) the complexity of the interactions between climate change and food production affects the overall understanding of their relations, (2) different actors in the food supply chain have a different impact on the UN Sustainable Development Goals (SDGs) when observed from the perspective of climate change. This is especially so in respect of SDG1 (No Poverty), and SDG2 (No Hunger) among many others.

2. Food production and climate change

Feeding nine to ten billion people by 2050 presents an enormous challenge. According to Godfray et al. (2010), several options have been proposed to help address the issue, including closing the yield gap (i.e. making the difference between the attainable yield and that realized smaller), increasing the production potential of crops (largely through the use of new technologies and investment in research), reducing waste, changing diets and expanding aquaculture. While increasing food production, we also need to significantly decrease the climate impact of food production as well as improve the resilience of food production to future environmental change. Additionally, non-climate related needs include protecting our freshwater resources, protecting biodiversity, moving towards healthier diets, and reducing the adverse impact of food production on a whole range of ecosystem services (WHO, 2004; FAO, 2010; Frenken and Kiersch, 2011; Bommarco et al., 2018).

Food production from agriculture is extremely dependent on temperature and rainfall and therefore is vulnerable to climate change. Climate change affects food production in complex ways (Donkor et al., 2019). Direct impacts include changes in agroecological conditions; indirect impacts include changes in economic growth and distribution of incomes, which in turn affect the demand for agricultural produce. As reported by Smith and Gregory (2013), the main drivers of agricultural responses to climate change are biophysical effects and socio-economic factors. Crop production is affected biophysically by meteorological variables, including rising temperatures, changing precipitation regimes, and increased atmospheric carbon dioxide levels. Socio-economic factors influence responses to changes in crop productivity, with price, production, and consumption changes, shifts in comparative advantage, the impacts on per capita energy consumption, and child malnutrition.

Climate change has affected food production, mostly through the impacts of unexpected extreme weather events across the countries that make a significant contribution to global food production, affecting global food security (Mbow et al., 2019). In addition, impacts of sea-level rise have affected the food production in low-lying coastal areas (Nunn, 2013; Gopalakrishnan et al., 2019), and the impact of increased CO_2 concentration has also affected food production and consumption (Lee et al., 2018).

Future changes in climate patterns coupled with population dynamics could result in higher vulnerability (Sala et al., 2017). In tropical latitudes, where much of the current food security problems exist, temperature increases are expected to be predominantly detrimental (FAO, 2017). Africa has food insecurity with recurrent droughts and increased desertification from climate change in the region, leading to increased malnutrition among the population (Besada and Werner, 2015; Donkor and Mearns, 2018). Extreme weather and sea-level rise have affected Africa and South Asia (Sasson, 2012; FAO, 2015). The temperature increase has shown an increase in the yields of certain crops including maize at higher latitudes, whereas the same crops may show a yield reduction in lower latitudes (Mbow et al., 2019). When the increased frequency of hot days due to climate change has reduced the yield of crops such as maize, the importance of having advanced technology has become inevitable to sustain yields at an acceptable level (Hawkins et al., 2013).

Empirical evidence suggests that increases in temperature in the period 1980–2008 have already resulted in average global maize and wheat yield reductions of 3.8 % and 5.5 %, respectively, compared to a non-climate change scenario (Lobell et al., 2011). To date, climate trends have been largely offset by gains derived from technology, carbon dioxide fertilization, and other factors (Lobell et al., 2011).

In summary, Nelson et al. (2009) found that: (i) climate change will cause yield declines for the most important crops in developing countries, with South Asia being affected particularly badly, (ii) climate change will have varying effects on irrigated yields, but yields for all irrigated crops in South Asia will experience large declines, (iii) climate change will result in price increases for rice, wheat, maize and soya beans (the most important agricultural crops) with higher feed prices resulting in higher meat prices, reducing the growth in meat consumption slightly and causing a more substantial fall in cereal consumption, (iv) food energy availability in 2050 will decline relative to 2000 levels throughout the developing world, which will increase child malnutrition by 20 % relative to a world with no climate change and nearly half of them will be in Sub Saharan Africa (Tirado et al., 2013); climate change will eliminate much of the improvement in child nourishment that would occur with no climate change (Lloyd et al., 2011).

Despite gains in some crops in some regions, under future climate change, the increased temperatures will eventually reduce crop yields but will encourage weed and pest proliferation, while changes in precipitation patterns will increase the likelihood of crop failures in the short term and a decline in production in the long term (Nelson et al., 2009). Climate extremes associated with future climate change (e.g., droughts, heatwaves, and storms) are also expected to adversely affect food production, but the impacts to date remain largely un-quantified. Since climate change is expected to adversely affect global food production, sustainable food production in the future will be even more difficult to achieve, making climate mitigation even more important. As shown in Fig. 1, climate change influences food production, and vice versa.

Globally, food consumption patterns have impacted food production and associated greenhouse gas emissions, which could feedback on the climate system. Consuming animal proteins such as beef is more GHG intensive per unit of consumption when compared to plant-based protein products (Carlsson-Kanyama and Gonzalez, 2009; Fresán and Sabaté, 2019). GHG emissions, which are mostly methane emissions and are associated with enteric fermentation in the livestock sector, depending on the feed quality, breed, and certain other factors (IPCC, 2006). The other emissions associated with meat production include those emissions associated with manure management, meat processing, transportation, etc. (Grossi et al., 2019). Such GHG emissions could enhance the anthropogenic climate change, which alternatively could feedback negatively on food production.

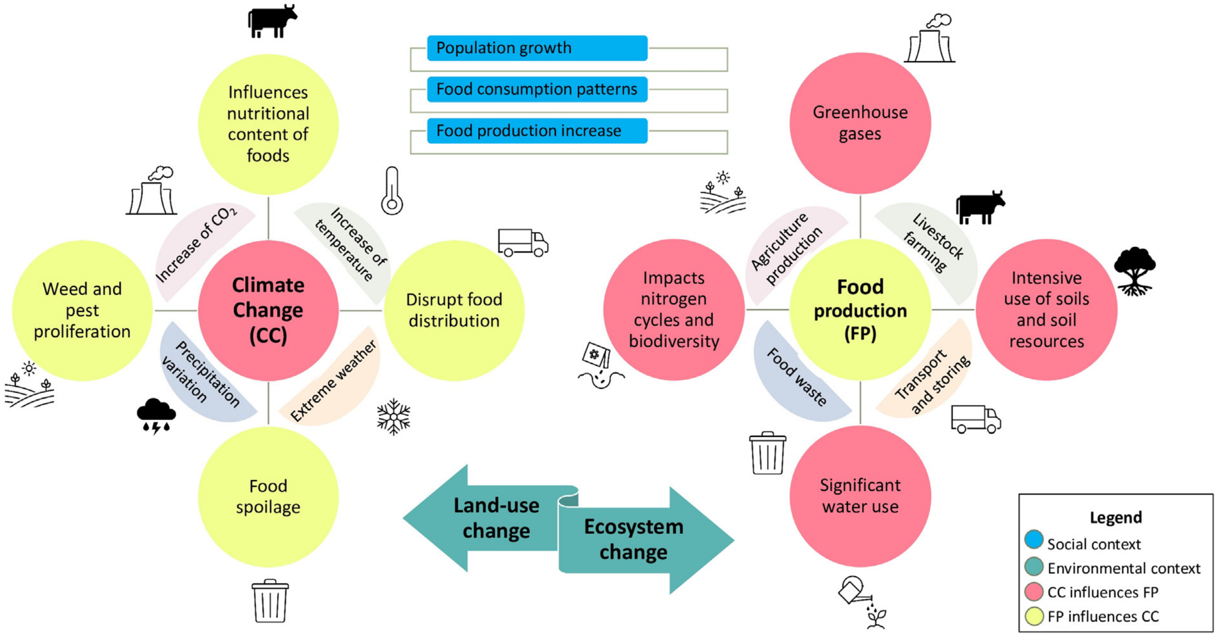

Fig. 1. Interface between climate change and food production. Source: Elaborated by the authors.

The energy use in food production/processing and transport also leads to GHG emissions (Crippa et al., 2021). For instance, consumption of locally produced food will contribute less to greenhouse gas emissions in comparison to food that is imported or transported from far away (Avetisyan et al., 2014). Climate-resilient adaptation and mitigation strategies that include policy interventions are needed to deal with the climate change impacts (Tirado et al., 2013).

Perennial vegetables are a neglected and underutilized crop species (NUCS). They represent 33–56 % of cultivated vegetable species and occupy 6 % of the world's vegetable cropland. Despite their distinct relevance to climate change mitigation and nutritional security, perennial vegetables receive little attention in the scientific literature (Toensmeier et al., 2020). Modern agricultural systems that promote the cultivation of a minimal number of crop species have relegated indigenous crops to the status of NUCS. The complex interactions of water scarcity associated with climate change and variability in sub-Saharan Africa (SSA) and population pressure require innovative strategies such as NUCS to address food insecurity and undernourishment (Chivenge et al., 2015). Food-based approaches that address malnutrition are disconnected from the current agricultural production system. Promising climate-resilient and locally available/adaptable NUCS are fundamental to improving dietary and production diversity to address hunger and malnutrition (Li et al., 2020).

3. Methods

To perform an overview, the (inter)link between climate change and food production was investigated through a bibliometric analysis. The keyword phrase “climate change and food” raised hundreds of thousands of publications at first glance (i.e., in the ScienceDirect search engine, over 195,000 results were reported). Since this topic is heterogeneously dispersed through various scientific publications (research and review articles, book chapters, conference papers, editorials, etc.), cascading the keywords to specific supply chain actors such as “climate change and agriculture” or “climate change and food transportation” still generated a large number of references. Therefore, the authors applied a text mining concept using the abilities of VOSviewer, a software tool used for bibliometric analysis, to gain a broad overview of the key focus areas in scientific literature (van Eck and Waltman, 2010). VOSviewer is often used to identify major thematic areas (and their interactions), thereby complementing review of scientific literature. The input data for this overview analysis was extracted from academic papers indexed in the Web of Science. To select relevant papers, a search string was developed to include two anchors of our overview – “climate change” and “food production” deployed to (“climate* change*” OR “global warming”) as first anchor and all actors in the food supply chain as the second (“agriculture*” OR “farming” OR “livestock product*” OR “food product*” OR “food processing” OR “food transport*” OR “food retail*” OR “food waste*” OR “food disposal*” OR “food sorting”). This search string was developed in an iterative manner to ensure adequate coverage of existing research on this topic. Upon checking the initial results, we noticed that other terms could be added to have better coverage. We continued this until adding more relevant terms did not result in the retrieval of more documents. This search revealed 7246 articles as of March 2021. Titles and abstracts of these papers were screened for suitability excluding the ones that do not truly reflect the scope of the work. Finally, 4881 articles were selected for final analysis. The screening was conducted manually. During this process, papers that were not directly related to the impacts of climate change on food production and vice versa were excluded.

Full record and citation data of the selected articles were downloaded for term co-occurrence analysis in VOSviewer. Using ‘all keywords’ as the ‘unit of analysis’ and ‘full counting’ as the counting method, an initial list of frequently co-occurred terms was obtained. More details about these processes can be found in the VOSviewer manual freely available at https://www.vosviewer.com/. Upon checking this initial list, was noticed that there are several synonyms that should be merged (e.g., climate change and climate-change). Therefore, using Microsoft Excel, a thesaurus file was developed to merge synonym terms. This thesaurus file was then added to the software and the analysis was run again.

The output of this analysis revealed a network of nodes and links, where node size is proportional to the frequency of occurrence and link width is proportional to the strength of the connection between two terms. Terms that co-occurred frequently established thematic clusters and indicated key focus areas (see Fig. 2). In addition, to gain a better understanding of the interactions between different sub-components, authors created more detailed term maps in the VOSviewer that was focused on more specific interactions (e.g., between ‘climate change’ and ‘livestock production).

Taking into account the objective of this paper, authors participated in a Delphi session to select most relevant UN SDGs associated with the results of the bibliometric analysis. This method is used to encourage experts in achieving consensus on a certain topic (Heiko, 2012). The session has

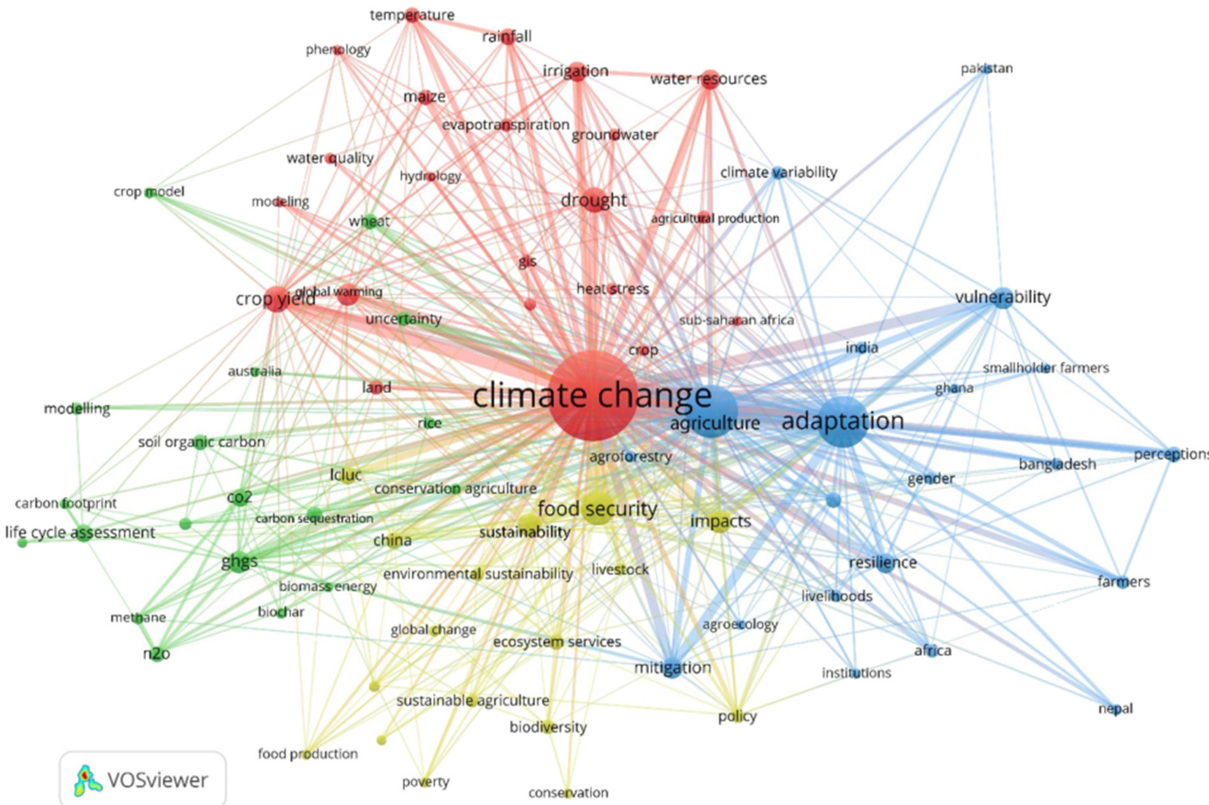

Fig. 2. The output of the term co-occurrence analysis.

been organized online and authors of this paper had the possibility to select three UN SDGs.

The novel aspects of this study are the fact that it explores the connection between climate change and food production against a background of supply chains. Also, it deploys a bibliometric analysis which sheds some light on the attention being given by the literature on the topic. Finally, the study produces some graphical illustrations which provide an overview of how food production and climate change are interrelated.

4. Overview of the outcomes from the bibliometric analysis

Results show that in addition to climate change and agriculture there are other terms included in the search string. Terms such as adaptation, food security, impacts, crop yield, drought, and vulnerability have received more attention. This clearly shows that research at the nexus of food and climate change is mainly focused on adaptation-related issues. Four clusters (in different colors) can be identified in the figure, and three of them (blue, red, and yellow) are mainly related to climate change impacts and adaptation strategies to mitigate risks, reduce vulnerability and increase resilience. Obviously, climate-resilient agriculture is essential for adaptation to climate change impacts. As expected, drought/water stress and heat stress are major impacts that have been discussed in the literature (red cluster). It is, however, worth noting that other climate impacts exist - such as storms - that may affect agricultural productivity. This may be a gap in the literature. The Fig. 2 shows that climate change impacts on the agriculture sector have mainly been discussed in relation to countries in Africa and South/Southeast Asia, being countries where agricultural production has been affected the most by climate change as discussed in Nelson et al. (2009) and Tirado et al. (2013). Closely related to the clusters on adaptation and impacts, there is a yellow cluster in which food security has a central position. This can be explained by the fact that climate change impacts may intensify environmental degradation (e.g., loss of biodiversity and ecosystem services) and thereby cause problems of food security.

Finally, there is a relatively smaller green cluster that is also not strongly connected to the other clusters. This cluster is clearly focused on climate change mitigation, and terms such as CO_2 and GHGs have a central position in it. Proximity and connection to terms such as land cover and land-use change (LCLUC) and life cycle assessment (LCA) indicate that agriculture was mostly the focus of LCA papers analyzing the (animal origin) food supply chain (Djekic and Tomasevic, 2016; Djekic et al., 2019a). Overall, it seems that climate change mitigation has received less attention than adaptation, and further research on mitigation is required. In addition, important search terms such as food waste, food processing, and food transport did not appear in the term map, and this may also show other potential research gaps that require further attention.

4.1. Efforts in reducing carbon footprints throughout the food supply chain continuum

4.1.1. Climate change and agriculture (and vice versa)

From the analysis of Fig. 3, three clusters emerge. One of the three clusters evidences the strong connection between climate change, impacts, crop yields, and temperature (red cluster). A second cluster relates agriculture, food security, and adaptation (blue cluster). This second cluster includes farmers, variability, and resilience. Climate change is related to the dimension of crops, irrigation, water resources, and productivity and the dimension of adaptation, farmers, and vulnerability. A third cluster (green cluster) deals with nutrients, carbon sequestration, sustainability, and biodiversity and ecosystems services. We can interpret this cluster as the interface between climate change, agriculture, and nature. These clusters correspond to the research of Niero et al. (2015) that emphasized the need to deploy food security scenarios to consider the effects of climate change on agricultural production, or to Porter et al. (2014), who pointed out the interconnection between climate conditions and crop productivity that is affected by factors such as type of crop and soil, climatic condition and agricultural practices.

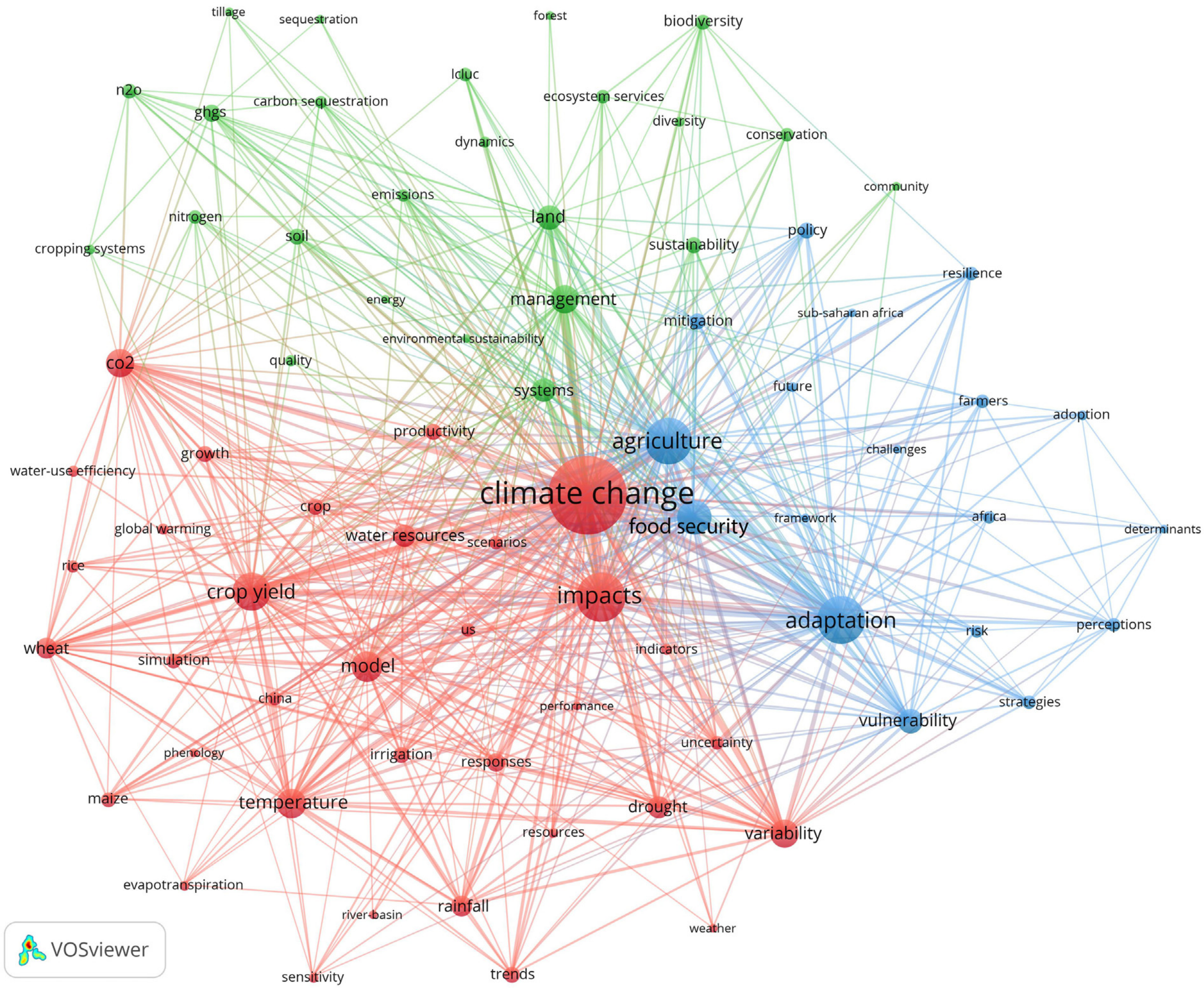

Fig. 3. The output of the term co-occurrence analysis for "Climate change" and "agriculture".

Factors that are associated with climate change effects at agricultural farms start with the variety of crops produced, the type of production system in place, chemicals such as fertilizers and/or plant protection substances used, and end with agricultural practices in place. Some mitigation strategies in agriculture include limiting disturbance to the soil by reducing the frequency and extent of cultivation to limit soil carbon loss and/or increase soil carbon storage. Management measures can also be introduced to limit biomass burning (Zaman et al., 2021). Nutrient deficient soils due to poor land-use lead to the clearing of more land for agriculture and the worsening of climate change (Ghahramani et al., 2020), so shifting to mixed crop-livestock systems is a sound mitigation measure.

An interesting study shows that climate-smart technologies may be efficient in targeting inputs to the fields, enabling the reduction of greenhouse gas emissions by introducing field monitoring (to reduce spoilage and crop waste) and compost management, and helping farmers and other stakeholders to adopt environmentally-friendly agricultural decisions (Panchasara et al., 2021).

4.1.2. Climate change and livestock production (and vice versa)

Farm-based livestock activities contribute directly to climate change due to enteric fermentation and manure management and indirectly through the production of feed (Röös et al., 2013; Gerber et al., 2015). Since farms are identified as one of the most contributing links to climate change in the food supply chain, a bottom-up approach in analyzing practices at farms should explore improvement techniques and mitigation strategies in combating climate change (Djekic and Tomasevic, 2020a). A nexus approach can enhance water, energy and food security by increasing efficiency, reducing trade-offs, building synergies and improving governance across sectors (Hoff, 2011).

Meiirkhanuly et al. (2020) investigated the effect of using two types of biochar (one highly alkaline and porous and another composed of corn stover and red oak) as a way to reduce emissions from pig manure. Depending on the type, there were observed decreases for methane (NH_3), p-cresol, and H_2S. The possibility of using bamboo biochar as a way to reduce gaseous emissions from poultry manure, that of nitrogen and carbon, was confirmed in the study of Awasthi et al. (2020). Chen et al. (2020) performed an assessment on the effectiveness of using chicken manure biochar and the chicken manure-integrated microbial consortium on compost maturity and in reducing greenhouse gases and ammonia. This study confirmed that the use of chicken manure biochar and chicken manure-integrated microbial consortium reduced the emission of nitrous oxide and methane.

Mostafa et al. (2020) showed that using slurry aeration as an approach to reduce gaseous emissions from pig manure reduced gas emissions of nitrous oxide and ammonia by over 10 %, and methane by over 50 %. Im et al. (2020) confirmed the potential of lowering the temperature of cattle manure as a catalyst to reducing the level of methane emissions. Anderson et al. (2020) showed that the treatment of poultry litter with different levels of aluminum sulfate could reduce ammonia emissions.

Gaviria-Uribe et al. (2020) conducted a study in which they investigated the association between nutrition and methane emissions from livestock, focusing on legume-based diets as a mitigation measure to reduce methane emissions. The modeling of feed, manure management, and the size of the herd can result in decreasing GHG emissions (Berhe et al., 2020). Options to mitigate GHG emissions in agriculture in Africa shows that advanced livestock breeding and feeding, organic nitrogen inputs, improved pastures, and shifting land-use practices all contribute to GHG emission reduction (Anuga et al., 2020). Finally, land-based mitigation activities introduced at the small-scale, rural landscape level can limit and offset the GHG livestock emissions of the same area, resulting in carbon-neutral livestock systems (Chiriacò and Valentini, 2021). The graphical illustration which provides interactions between 'climate change' and 'livestock production' is provided as supplementary material.

4.1.3. Climate change and food processing (and vice versa)

From Fig. 4 a first cluster clearly evidences the relations between climate change and food security (green cluster), which is separated from a cluster that relates life cycle assessment to the environmental impacts and sustainability (that interconnects with sustainability in the first cluster) (red cluster). The life cycle assessment clusters bring together food processing, consumption, and food waste. Two small clusters that interpenetrate also interconnect with agriculture and impact with the other two described clusters. This analysis shows an interesting phenomenon: that food processing is more associated with food security/food sustainability than with the impact on climate change. The first reason is that food processing is not recognized as a big climate change polluter (Djekic et al., 2014; Djekic and Tomasevic, 2020a). The second reason is that after food processing, the products are distributed and/or sold, thereby affecting food security. Finally, this link of the food supply chain with its sustainable effect contributes to sustainable food production. Augustin et al. (2016) stress the role of food processing in food security, striving towards sustainable production and reducing food waste.

From a life-cycle assessment (LCA) point of view (ISO, 2006), food processing plants are considered as "gate-to-gate" parts of the food supply chain. In terms of analyzing GHG emissions on an organizational level as outlined in ISO 14064 (ISO, 2018), food-processing plants have much higher indirect GHG emissions (caused by operations and activities that arise from GHG sources not owned by food companies – Scope 2) than direct emissions (from GHG sources owned by processing plants – Scope 1). In that sense, mitigation activities are focused on optimizing production and natural resource consumption (Schulman et al., 2021).

In the animal origin food sector, improvement alternatives include optimizing cleaning and sanitation with environmentally friendly chemicals to avoid solute wastewater discharge, optimal product changeovers to minimize the use of water and cleaning agents, the use of optimal packaging materials with low carbon footprints when disposed of, and the implementation of energy management – all decreasing indirect emission of GHGs (Skunca et al., 2018; Djekic et al., 2019a; Djekic and Tomasevic, 2020a).

Also, for maintaining the cold chain within the processing plant, the use of lower global warming potential refrigerants is an alternative (Yang et al., 2021). Actions needed for reducing GHG emissions in the food service sector (restaurants, canteens, or catering) comprise the following: menu design (promotion of sustainable diets), purchasing of raw materials from local/seasonal producers (possibly organic food), innovative kitchen technologies that are energy-efficient joined with optimal waste management, and awareness training of staff (Lund-Durlacher and Gössling, 2020).

4.1.4. Climate change and (food) transportation (and vice versa)

From Fig. 5 four clusters can be considered. A first cluster reveals a pattern that we saw in Fig. 4, showing a clear relationship between climate change and food security (green cluster). An opposite cluster (red cluster) cluster reveals a pattern that we saw in Fig. 4 showing a clear relation between life cycle assessment, carbon footprint, and sustainability. The above cluster (blue cluster) evidences the relations between transport, emissions, policies, and mitigation. The main reason for the connection of

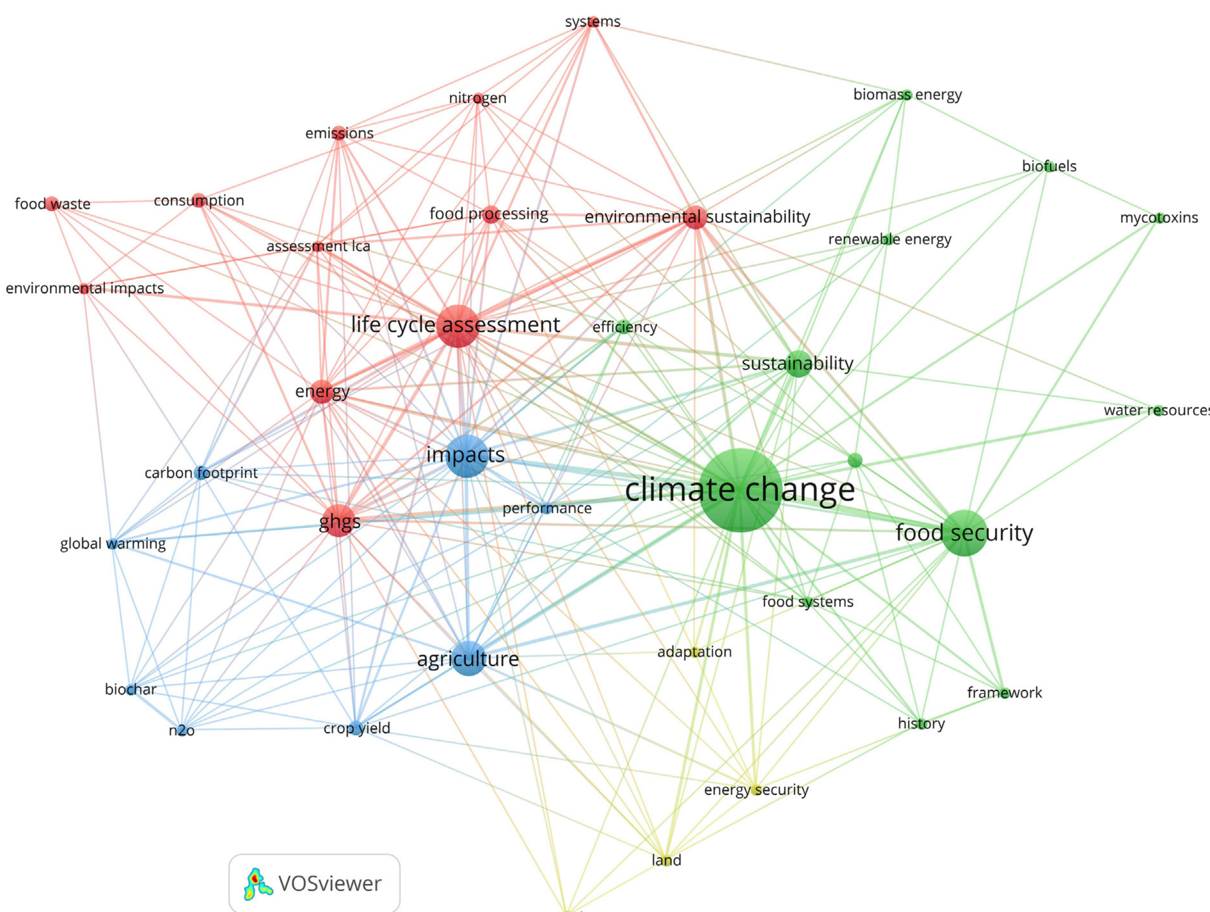

Fig. 4. The output of the term co-occurrence analysis for "climate change" and "food processing".

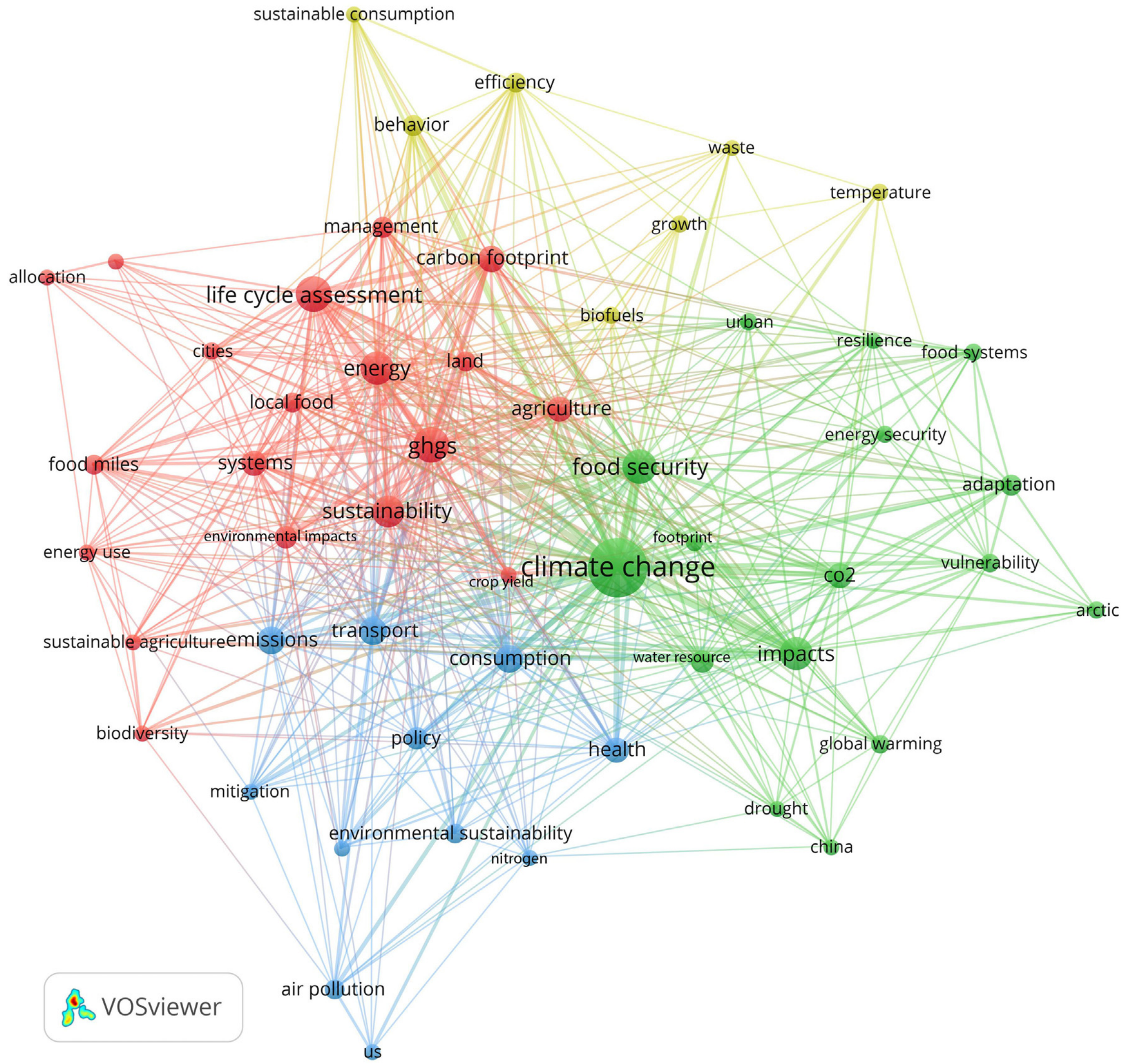

Fig. 5. The output of the term co-occurrence analysis for "climate change" and "food transportation".

LCA and food transportation is that food transportation occurs in all stages of food production from farms to consumers.

Climate parameters caused by climate change (precipitation, high/low temperatures, thunderstorms, winds, and restricted visibility caused by fog, dust, haze, or smog) result in the following impacts on transportation systems: transportation delays, re-routing, and re-scheduling, reduced speed, pressure on tires, stress on infrastructure/vehicles, road/railway closures, vehicle instability (Wang et al., 2020). Basic strategies in combating climate change effects on the transportation sector are comprised of adaptation and mitigation actions. Studies on climate change and food transportation identify the reduction of greenhouse gases (GHGs) from the vehicles to the air joint by using low carbon fuels as a basis for climate-friendly transportation policy (Boarnet, 2010). Besides transportation systems, it is important to mention that infrastructural factors such as age, location, and maintenance also play a role in mitigation strategies (Strauch et al., 2015; Kriewald et al., 2019; Pradhan et al., 2020).

When it comes to analyzing food transportation from the processing plant to consumers, two types of transportation routes should be considered: (i) transportation of food from a food processing plant to retail; (ii) transportation of food from retail to households. A case study on analyzing the transportation impact of dairy products produced and sold locally as opposed to cross-country distribution revealed that the "food-mile" concept linked with climate change is not sufficient in interpreting climate impacts, since other different factors influence transportation impact in terms of energy use and emissions per functional unit (Djekic et al., 2018). The main conclusion was associated with the optimization of transportation routes (performed by big dairy companies) that have the potential of decreasing the carbon footprint per product. López-Avilés et al. (2019) analyzed a case study of bread distribution in the UK. They proposed the main improvements as transportation of bread from baking plants to retailers using electric vehicles and optimizing the truck-loading ratio. However, since an average shopping travel distance is more than 750 km/year/household (with almost two-thirds performed by car), one of the main strategies should be the promotion of walking or cycling to buy bread from local bakeries. This concurs with the findings of Zhang and Mao (2019), that three transportation modes enable access to food by consumers - traveling by car, bicycle, or foot.

It is known that some animal-origin food commodities need to be transported while maintaining the cold chain regime in terms of optimal time/temperature ratio by using different types of trucks and refrigerators (Djekic and Tomasevic, 2020a). James (2019) proposed the promotion of the Internet of Things as a concept that can increase connectivity by using wireless sensors and networks, enabling greater traceability and monitoring during transport and better control in terms of optimizing energy consumption and carbon footprints. Finally, from a holistic point of view, Paiho et al. (2021)'s analysis of transportation/food solutions in circular cities identified carbon-free transportation by using electric bicycles/cars as a top priority.

4.1.5. Climate change and food storage/retail (and vice versa)

In Fig. 6, there is a clear opposition between the two clusters. A green cluster and a red cluster - as shown before (Figs. 4 and 5) - interconnect life cycle assessment, food waste, emissions, and carbon footprints. A third cluster (blue cluster) brings together for the first time the issues of consumption, nutrition, and obesity. Another novelty in Fig. 6 is the connection between supermarkets and supply chain management. One of the reasons for such a diverse cluster distinction is that retailers on the one hand play a role in supplying food to consumers, while on the other, they discard spoiled/unsold food after shelf life, creating more food waste at a late stage of the supply chain (Buisman et al., 2019).

Regarding retailers, and besides food waste, one of the environmental impacts is associated with the use of refrigerants for maintaining the cold chain. These temperature chains are vital for keeping food safe since inadequate temperatures trigger the growth of potentially harmful microorganisms (Sofos, 2014). Besides temperature, factors to be considered include the time/temperature ratio and the kind of refrigerators used (Zubeldia et al., 2016). Impacts are linked with global warming and ozone layer depletion occurring throughout the entire food supply chain but are mostly associated with storage/retail (Djekic and Tomasevic, 2016).

In their study, Hart et al. (2020) considered a modeling framework for maximum investment strategies that support the food retail industry in shifting from hydrofluorocarbon (HFC) refrigeration systems to lower GWP systems by 2030, in line with EU legislation, resulting in up to a 70 % annual reduction in yearly carbon emissions by 2030. Some authors, like Wang et al. (2021), propose defining a clear refrigerant dosage scheme for future refrigerant replacement phasing-out. Sanguri et al. (2021) investigate barriers to adopting low GWP refrigerants in India as a developing country, emphasizing the role of governmental support.

An interesting alternative is the use of CO_2 as an alternative refrigerant for supermarket refrigeration systems, proposing a resistance-capacity model structure (Sun et al., 2021). It hypothesizes that semi-thermodynamic models can estimate reciprocating compressors' volumetric efficiency and power consumption. Another engineering approach was observed in a study by McLinden et al. (2020). This study investigated design approaches for mitigating climate change by looking at the vapor-compression cycle, since current promising refrigerants such as fluorinated olefins, known as hydro fluoro olefins (HFOs), are more flammable, causing trade-offs between safety and environmental benefits. Therefore, a renaissance of "natural refrigerants" (ammonia, carbon dioxide, propane, and isobutane) with an innovative system design may reduce the required quantity of refrigerant and allow for a wider choice of refrigerants. Finally, improved storage practices have the potential to maximize the supply chain network design, and facilitate more effective climate change effects (Burek and Nutter, 2020).

4.1.6. Climate change and food waste (and vice versa)

Fig. 7 is a complex one, revealing four clusters that interconnect and interpenetrate. Food waste is central to a first cluster (red cluster) and, as seen before, relates to climate change, impacts, waste, and sustainability, but also behavior. A blue cluster integrates the issues of technology, management, and incineration, which interpenetrates a third cluster (green cluster) where life cycle assessment, management, carbon footprint, and efficiency are included. A fourth cluster (yellow cluster) includes and relates the issues of anaerobic digestion, biofuels, co-digestion, and biogas production. From a life-cycle perspective, food waste may occur in any stage of the food chain continuum, from primary production to households and food consumption, whereas households are recognized as the most important contributors as the final link in the chain (Priefer et al., 2016; Djekic et al., 2019b). When

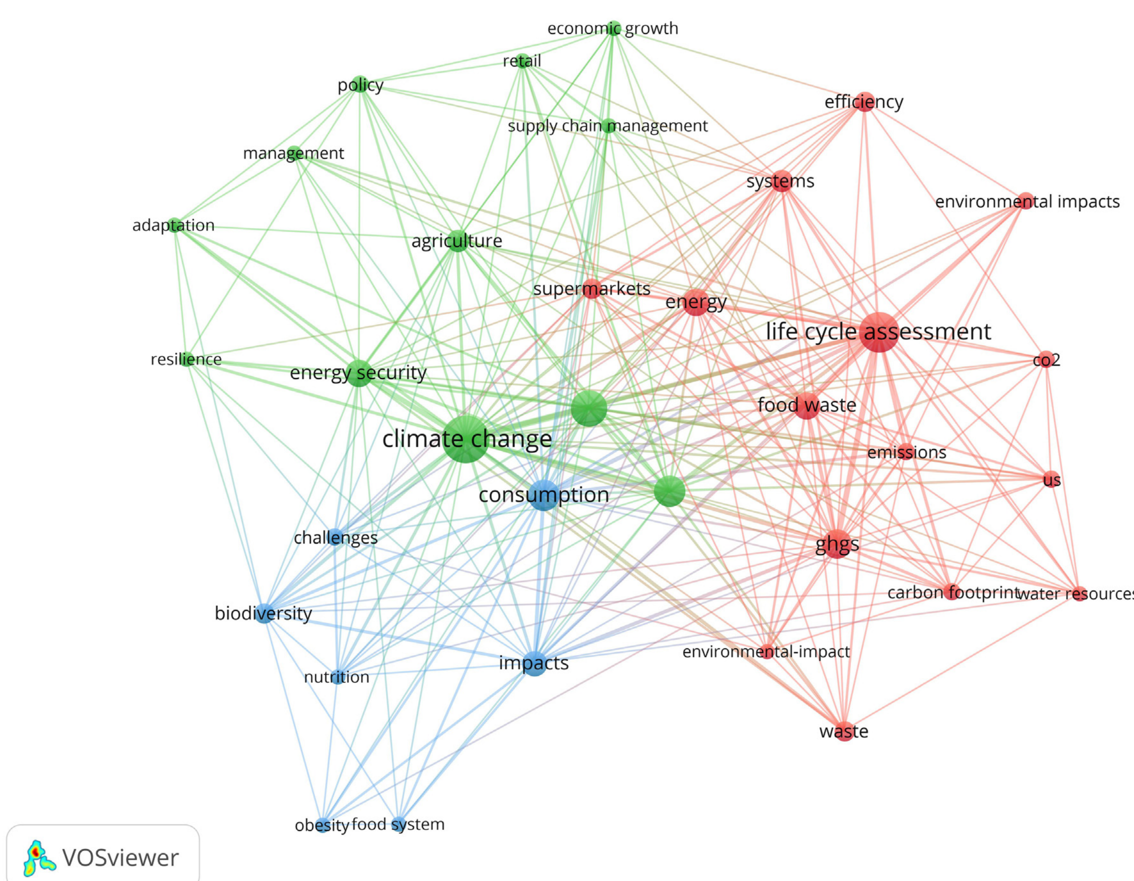

Fig. 6. The output of the term co-occurrence analysis for "climate change" and "food retail".

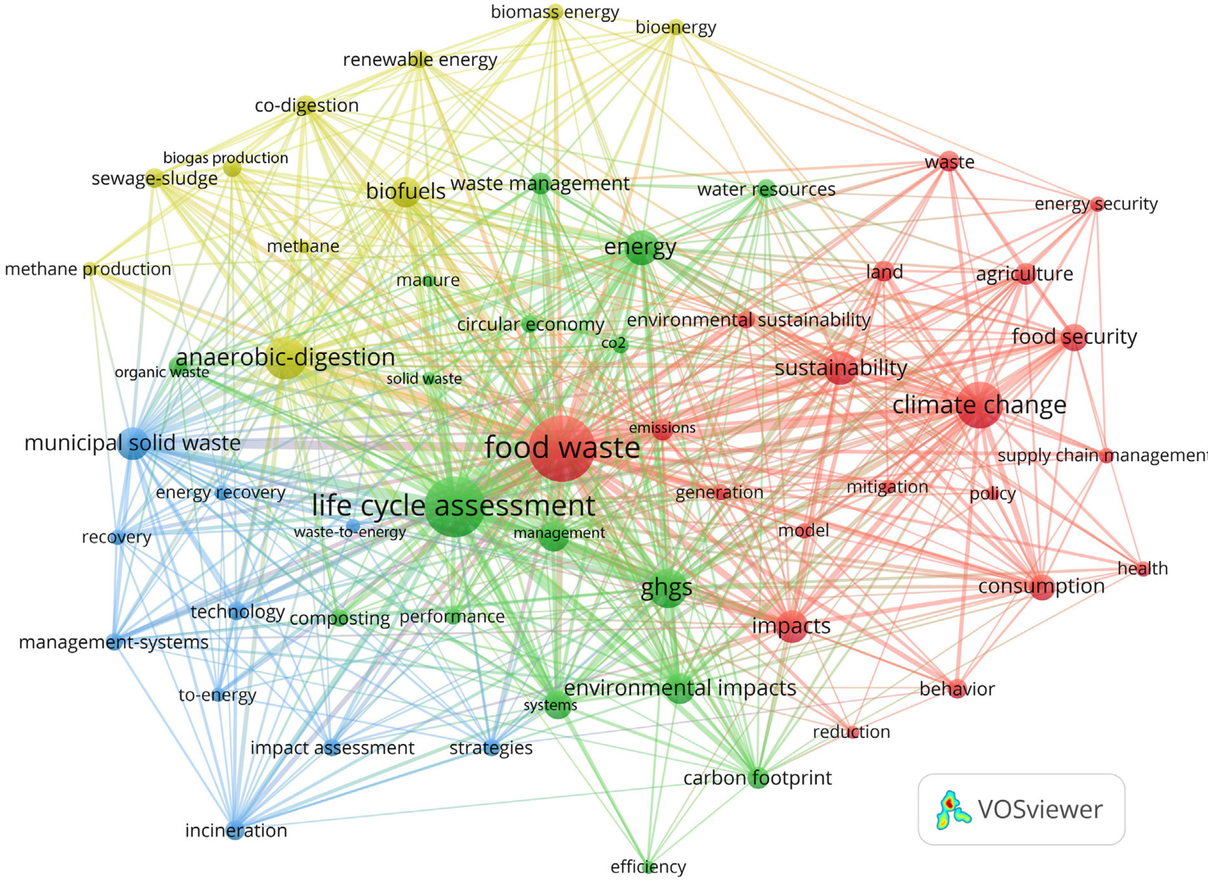

Fig. 7. The output of the term co-occurrence analysis for “climate change” and “food waste”.

occurring in households, the behavior of food consumers is the trigger for discarding food waste but also for environmental-friendly behavior (Aschemann-Witzel et al., 2021).

At the primary stage, Grigatti et al. (2020) evaluated composted food waste anaerobic digestors, confirming that this waste treatment reduces CO_2 emissions and can be an alternative option to reduce GHG emissions without affecting the nutrient levels of wastes. Also, Keng et al. (2020) evaluated the possibility of using a community-scale composting approach in the management of food waste. The elements of the approach include an open static pile, food waste as a substrate, and leaf litter applied as a bulking agent. According to the authors, the benefits derived from using this approach are that it reduces gaseous emissions while also providing organic fertilizer.

The comparison by de Sadeleer et al. (2020) of the performance of two food waste management approaches - anaerobic digestion and incinerations - showed that anaerobic digestion led to a reduction in GHG emissions when compared to incineration. On the contrary, incinerations yielded better energy efficiency than anaerobic digesters. Park et al. (2021) proposed an approach for food waste management whereby co-pyrolysis from food waste is mixed with lignocellulosic biomass from wood bark in a continuous flow pyrolysis reactor. Results revealed that a mixture of lignocellulosic biomass and food waste can increase the yield of H2, with a reduction of phenolic compounds and indirectly decreasing climate change. Ortigueira et al. (2020) evaluated a food waste biorefinery using an acidogenic fermentation approach mixed with carbon dioxide sequestration to convert food waste into Hydrogen (H2). In a scenario where the authors considered the reuse of fermentation sludge as a source of nitrogen within the acidogenic fermentation, global warming potential emissions were reduced by over 60 %, so upscaling this approach has the potential to reduce emissions from food waste. Elginoz et al. (2020) proposed an innovative food waste management approach using a homogenization reactor, fermenter, and a centrifuge to convert food waste into volatile fatty acid supernatant; such a system can reduce ozone depletion.

When it comes to household food waste, the main strategy is prevention in terms of purchase and meal preparation by jointly planning the management of plate leftovers and the regular checking of food expiration dates (Schanes et al., 2018). Djekic et al. (2019b) showed that addressing social habits and raising awareness among household members is most important in reducing food waste in households. A focus on personal emotions associated with food consumption and guilt related to discarding food waste together with improved household food management from purchasing to food preparation paves the way for reducing GHG emissions of food waste (Djekic et al., 2019c).

5. Discussion

The bibliometric analysis has shown that connections with climate change are often made through food security and agricultural yields. These, in turn, may be associated with the following SDGs 1, 2, 3, 6, 7, 12, 13, 15. The list of SDGs is not meant to be too comprehensive but focus on those most closely related with the topic. As a result of the Delphi session, authors have selected the following UN SDGs as most important: SDG2 – ‘Zero Hunger’, focuses on the influence of temperature on heat stress and animal welfare affecting poor farmers linked with UN SDG1 – ‘No poverty’; SDG 15 – ‘Life on land’ due to the connections with the use of land resources; and SDG13- ´Climate Action´ based on the need to reduce CO_2 emissions and assist with climate change mitigation.

These findings concur with the FAO message on UN SDGs. The second level of connection (through identified clusters) interlinks climate change with sustainable (agricultural) production (UN SDG12 – ‘Responsible consumption and production’), with a focus on Africa and South Asia.

The next stage in the food supply chain (food processing) connects clusters with food security (UN SDG2), and life-cycle assessment as a methodology for understanding the environmental / sustainability impact of processing food leaning towards sustainable production (UN SDG12). As good hygiene practice (CAC, 2020) is a mandatory requirement in all food processing facilities, cleaning, and sanitation associated with the use of potable water is another perspective associated with UN SDG6 - 'Clean water and sanitation' (Djekic and Tomasevic, 2020b).

After the produced food starts its life cycle on the market (e.g. production) it is traded and transported to the customer. The cluster analysis here mentioned food security (UN SDG2), which connects this stage with sustainable consumption (UN SDG12), nutrition and obesity associated with UN SDG3 – 'Good health and well-being and need for environmentally friendly energy sources for transportation (UN SDG7 - 'Affordable and clean energy'). The contribution of more sustainable approaches to agriculture and making it more resilient to climate change may support current efforts to increase the food security of rural communities and, inter alia, the fight against poverty and hunger. Bibliometric analysis confirms the link of this stage to UN SDGs similar to the work of (Djekic et al., 2021). In the final (consumption) stage, food waste is linked with climate change in terms of sustainable diets (SDG 2 and 3) and consumption (SDG12). Concerning the relationship between food processing and waste reduction presented in 4.1.3, it is essential to highlight that as part of the discussion on reduced food production and hunger; there are also debates on the severe global threat to public health posed by the consumption of ultra-processed food. This type of food is associated with obesity and a variety of other diseases related to poor diets.

This bibliometric analysis highlights the following trends: (i) the majority of publications are focused on analyzing impacts of food production on climate change with limited papers (mostly in the primary stage) analyzing impacts of climate change on food production; (ii) there is a disbalance in favor of analyzing primary production (at the agricultural stage) opposed to the other stages of the food supply chain continuum; (iii) there is a disbalance in favor of more publications with carbon footprint data opposed to limited papers with mitigation strategies on combating climate change (from a food production point of view), (iii) life-cycle methodology is the most accepted method for analyzing carbon footprint of food production; (iv) geographically, the impact of the primary sector is mainly analyzed in Africa and South Asia, while other stages are more analyzed in case studies from developed countries.

5.1. Climate change in the food supply chain continuum

Fig. 8 depicts the main mitigation strategies in combating climate change throughout the food supply chain continuum, as identified in the previous sections. It provides valuable insight into the current strategies employed by scholars and industry, as well as the potential of exploring new ideas.

The complexity of the food supply chain is once more proven in the figure, showing different approaches at different parts of the supply chain. However, the promotion of such a holistic approach, as provided in this review paper, paves the way for future research.

6. Conclusions

As this paper has demonstrated, the entire food supply chain is recognized as a contributor to climate change. Climate-resilient agriculture is essential for adaptation to climate change impacts. In addition, the complexity of the food supply chain suggests that holistic approaches are needed to address the many challenges. Moreover, the interaction between climate change and the food supply chain is complex and overlaps many dimensions. This overview showed that more publications analyze the impact of food production on climate change (than vice versa) confirm the first working hypothesis.

As primary production (crop/livestock production) is the weakest link in the chain yet has the highest interaction with climate change, a bottom-up approach that analyzes farm practices, and consequently the path from the farm to the fork, could be of added value in the exploration of improvement techniques. This paper confirms that primary production was more focused as opposed to other actors in the supply chain and that this stage has higher impacts on climate change.

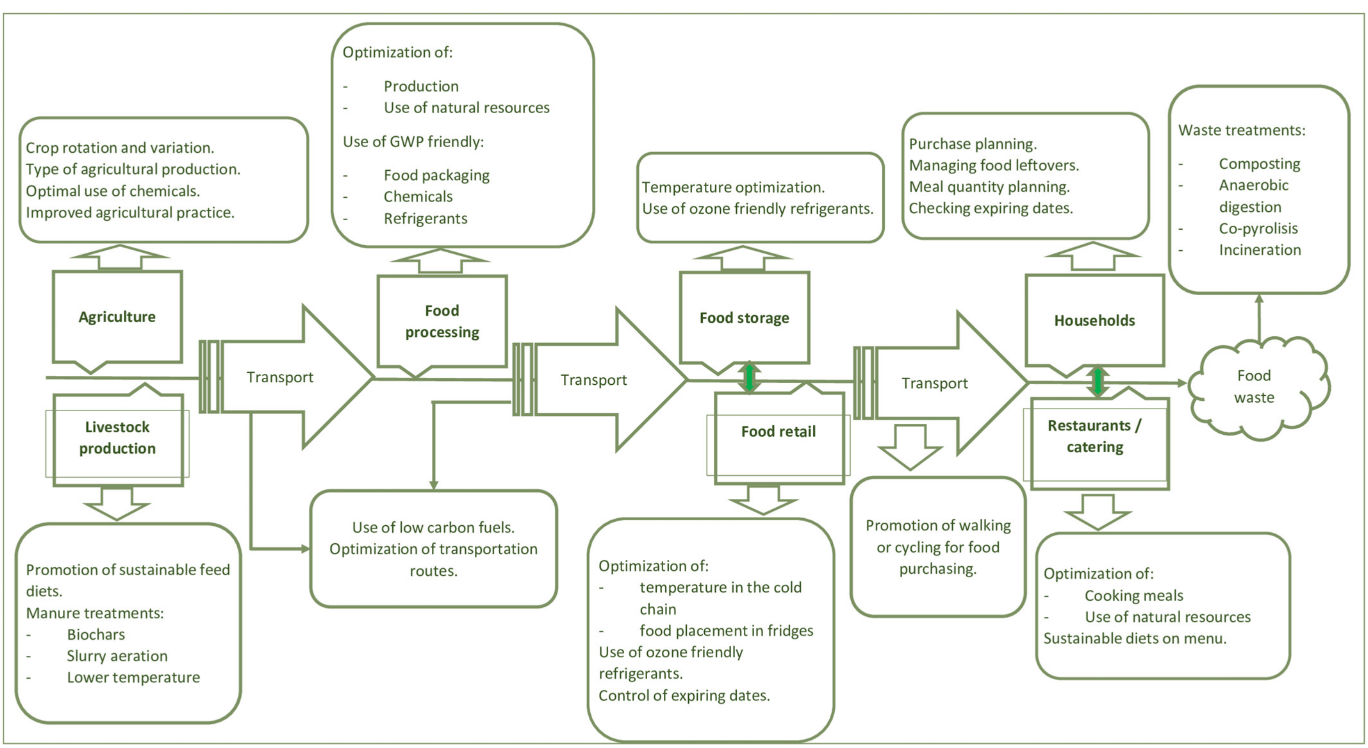

Fig. 8. Main mitigation strategies in combating climate change throughout the food supply chain continuum. Source: Elaborated by the authors.

Although eight UN SDGs have been associated with the interaction of food production and climate change, three of them are associated with all stages (UN SDGs 2, 12, and 13) while the others are linked with some of the actors in the food chain. This confirms the second working hypothesis that different actors have a different impact on the SDGs.

This paper has two main limitations. The first is that the bibliometric analysis focused on aspects related to climate change and food production, with a lesser focus on the overall environmental impacts of the use of pesticides or monocultures. Secondly, whereas it touched upon the subject matter of the role of consumers, it did not dwell deep enough on this topic, for which a different study is being carried out.

Despite these constraints, the paper provides a contribution to the literature in the sense that it sheds some light on the contributions of food production to climate change, illustrating the various factors associated with it.

In general, areas for further research highlighted by this study in terms of climate adaptation and mitigation include the fields of food waste, food processing, and food transport. Farm-based livestock activities exacerbate climate change due to enteric fermentation, manure management, and production of feed, which require novel improvement techniques and mitigation strategies. Furthermore, the employment of lower global warming potential refrigerants will help in limiting GHG emissions in the foodservice sector. In addition, optimizing transport routes can help limit the carbon footprint per product in the food industry. Addressing social habits and increasing awareness is critical to reducing food waste discarded from households.

Taking into account that the war in the Ukraine has severely damaged its wheat reserves and their export (FAO, 2022), it is expected an exacerbation of food insecurity will be seen in the poorer parts of the world, especially in Africa.

Combating climate change in the food supply chain continuum requires synergy by all interested parties - from food producers and traders to policymakers and final consumers. It is also expected that scholars and academia will contribute by undertaking research that seeks climate-friendly food production solutions.

CRediT authorship contribution statement

Walter Leal Filho: Conceptualization, Methodology, Writing - Original Draft, Writing, Reviewing and Editing, Project administration. **Andréia Faraoni Freitas Setti:** Visualization, Supervision, Investigation, Writing, Reviewing and Editing. **Ulisses Miranda Azeiteiro**: Supervision, Methodology, Writing, Reviewing and Editing. **Erandathie Lokupitiya**: Investigation, Writing. **Felix Kwabena Donkor**: Investigation, Writing, Reviewing. **NseAbasi NsikakAbasi Etim**: Investigation, Writing. **Newton Matandirotya:** Investigation, Writing, Reviewing and Editing. **Felicia Motunrayo Olooto:** Investigation, Writing. **Ayyoob Sharifi:** Investigation, Writing. **Gustavo J. Nagy**: Reviewing and Editing. **Ilija Djekic:** Formal analysis, Visualization, Supervision, Writing, Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.156438.

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