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How Can Climate Change Impact Human Health via Food Security? A Bibliometric Analysis

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Abstract: Global climate change, induced by anthropogenic causes, has severe consequences for Earth and its inhabitants. With the consequences already visible around the globe, one of them is the impact on food security. The lack of food security has serious impacts on health, especially in vulnerable populations who highly depend on a nutritious diet for a healthy life. The following research aims to assess the current research status of climate change, food security and health. In this context, the interlinkage of the three key concepts is analyzed, as well as the related health consequences. To achieve the aims of this research, a bibliometric analysis was conducted using VOSviewer, (version 1.6.16) including 453 papers. The data were retrieved from the Scopus database on 10 November 2022. Bibliometric analysis can illustrate emerging and key topic areas using keywords and co-occurrence analysis; hence, it is an adequate method to meet the listed research aims. Five different clusters have been derived from the analysis, each representing a different perspective on interlinkage. From the different clusters, the main consequences of climate change on food security could be derived, such as a decrease in crop yields, less availability of fish and livestock, or food contamination through mycotoxins. These can cause serious health implications, predominantly increasing the rate of malnutrition globally. The work showed the importance of action to prevent the consequences of climate change in relation to food security and health nexus. To do so, adaptation strategies are needed that consider the interdisciplinary scope of the problem, building sustainable measures that benefit each concept.

Keywords: climate change; food security; health implications; vulnerable populations; adaptation strategies

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1. Introduction

Climate change has numerous consequences on the Earth and the existing ecosystems within, such as floods, heatwaves, extreme weather events and droughts, which are likely to increase in severity and frequency in the years to come [1]. Those consequences indirectly affect food security, for instance, heatwaves, which greatly affect crops, diminishing yields by up to 16% as a consequence of the European heatwave in 2022 [2]. On the other hand, floods lead to serious damage to crops and affect livestock production [3]. Among other things, climate change contributes to the extinction of marine mammals due to warming temperatures, which causes disturbances in the fishing industry [4]. These consequences pose a significant risk to food security.

The most recent definition in the FAO [5] Food Security and Nutrition report goes as follows: "A situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life. Based on this definition, four food security dimensions can be identified: food availability, economic and physical access to food, food utilization and stability over time" and "The concept of food security is evolving to recognize the centrality of agency and sustainability" [5,6]. The concept of food security encompasses six dimensions (see Figure 1), four of which were recognized by the FAO until 2021. The four previously recognized dimensions were food availability, accessibility, and utilization and the stability of these dimensions formed the fourth one. However, sustainability and agency were discussed among scholars as a fifth and sixth dimension to add [6] and have been recognized by the FAO in their recent report [5]. While the number of undernourished people fell initially in 2005, it has been increasing again since 2014, to around 800 million people undernourished in 2021 [7].

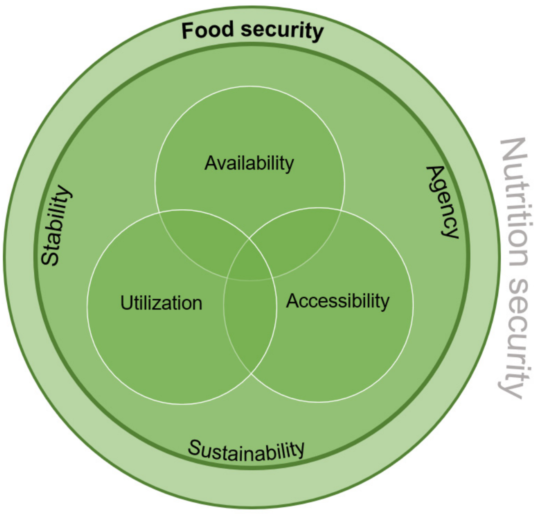

Figure 1. Food security dimensions; authors' elaboration based on [5].

The consequences of food insecurity can be severe and diverse, such as on human health. For instance, implications in adults can include higher risks of developing mental health issues like depression, oral health problems, iron deficiencies, diabetes, a weakened immune system or generally poorer health status [8,9]. In children, food insecurity can raise the odds of development issues [8]. Apart from the health consequences mentioned, the impact of food insecurity can be far-reaching—it can influence the economy due to high healthcare costs relating to the previously mentioned health consequences or a general lower productivity in people affected by food insecurity. The Iowa Food Bank Association estimated this loss to be up to USD 130.5 billion annually [10]. Also, the socio-political situation can be affected by an increase in the risk of conflict. For example, some scholars believe that food insecurity influenced the Arab Spring revolution in 2011 [11,12]. Vulnerability to food insecurity can be influenced by various factors, such as physical, political, environmental and sociocultural [13]. The influence of these factors varies across countries and regions [14].

As stated in the famous proverb "You are what you eat", food is a fundamental part of human life. Whether it is for cultural reasons, a social experience, or the most essential part—providing nutrients and substantially influencing one's health—humans need food to survive and flourish. Therefore, food security is an important topic for human health. A healthy, diverse diet is a protective factor for one's health, diminishing the risk of non-communicable diseases such as diabetes and strokes, as well as strengthening the immune system and even impacting mental health, i.e., via the gut–brain axis [15]. If this diet is endangered by food insecurity, then likewise is one's health. Despite the common usage of the term "health" in everyday language, the definition and meaning vary. The probably most used definition is the one by the WHO: "Health is a state of complete physical, mental and social well-being and not merely the absence of disease or infirmity" [16]. This definition, however, has been a matter of discussion for different reasons, such as being too unrealistic to be reached or too binary [17]. Consequently, researchers have offered other definitions, and the present research uses the term human health as defined by Last [18], where human health is "A sustainable state of equilibrium or harmony between humans and their physical, biological and social environments that enables them to coexist indefinitely" and a "A structural, functional and emotional state that is compatible with effective life as an individual and as a member of family and community groups", with considerations of the environment and sustainability as well as many former critiques on other health definitions, like those of binarity and absoluteness [17].

In conclusion, understanding the impacts of climate change on food security outcomes is essential for analyzing the health impacts that might occur. Thus, this knowledge is strategically needed to help mitigate health risks by creating needs-based adaptation strategies. To underscore the importance of this issue, many international associations have acknowledged the risks: the Global Commission on Adaptation released a report in 2019 analyzing the linkages between food security, environment and adaptation, calling for more climate resistance [19]. Funding organizations such as the Global Environment Facility have equally added this linkage into their agenda [20].

To gain the above-mentioned knowledge, this research aims to fill these research gaps by answering the following questions:

1. Based on the current research status of the literature, how are the three key concepts (climate change, food security, and health) linked to each other?
2. What are the health consequences related to food insecurity driven by climate change?

2. Methods

2.1. Data Collection Strategy

To conduct a bibliometric analysis, data need to be collected in the form of academic sources relevant to the topic of research, here that is climate change, food security and its impact on health. The search string used (see Table 1) contains the most important keywords relevant to the research, which were previously identified with the help of narrative literature research. Different approaches were used to find the most fitting search string with sources relevant to the research aims; however, a fractional search for each food dimension resulted in a low number of sources and was, therefore, unused. The Scopus scientific database was chosen because of its large inclusion of various sources. The search was conducted on 10 November 2022 and resulted in 480 papers. This initial number was further reduced by applying inclusion criteria to filter out irrelevant sources. The exclusion criteria are listed in Table 1. After applying the inclusion criteria, a final number of 453 papers were selected for the download of their bibliographic data.

Table 1. Search strategy. The operator "*" searches for the keyword with different ending letters.

Search String	Inclusion Criteria	Number of Documents
TITLE ("climat * change" OR "global warming" OR "greenhouse effect" OR "changing climate" OR "greenhouse effect" OR "climatic change" OR "extreme weather" OR "climat * variability" OR "warm clima *" OR "climat * extreme *" OR "extreme climate" OR "greenhouse warming" OR "climate disaster *" OR "climat * effect" OR "Paris Agreement") AND TITLE ("food security" OR "food insecurity" OR "food availability" OR "food access *" OR "food utilization" OR "food sustainability" OR "food agency" OR "food stability" OR "food safety" OR "nutrition") AND ("public health" OR "global health" OR "disease *" OR "illness" OR "mental health" OR "physical health" OR "health *")	▪ English Language ▪ Article, Book Chapter, Review, Editorial, Conference Paper or Book	453

2.2. Data Analysis Strategy

Bibliometric analysis is increasingly being used in scientific research. The quantitative method handles a large amount of data in the form of academic sources [21]. The data can be processed using bibliometric analysis software to show their various features. The data were inserted into the bibliometric software VOSviewer. Term co-occurrence analysis was used in the following due to the nature of the research.

Co-occurrence analysis shows the relatedness of keywords within the dataset. The network visualization of the co-occurrence analysis, which is used in this research, presents the terms by label and in a circle. The bigger the circle appears, the more the term occurs within the used dataset, while the colours and location of the circles in the map represent their relatedness to each other. The closer they are, the more related they are in the dataset, while the colours represent the different thematic clusters to where the term belongs [22]. Moreover, to enhance the quality of the keywords, a thesaurus file was created after the initial analysis to avoid the doubling of keywords, i.e., *maize* and *Zea mays*. The thesaurus file was then added to the analysis, which resulted in the final bibliographic map.

3. Results and Discussion

Following the methodology described above, Figure 2 represents the final figure created via VOSviewer. A total of 97 keywords can be found in the graph, divided into five main clusters.

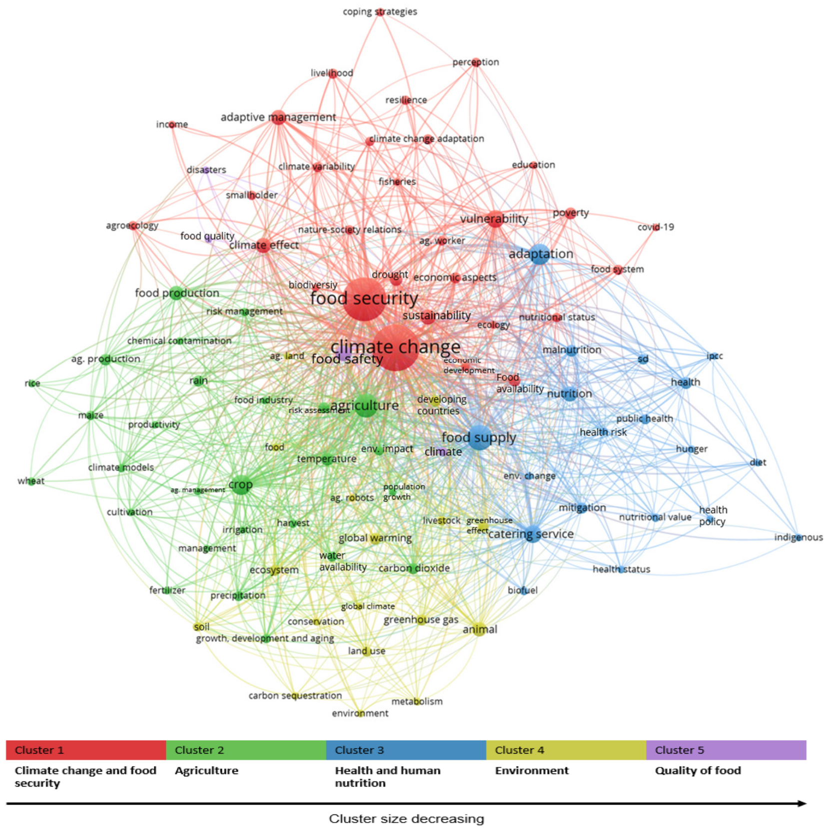

Figure 2. Bibliometric analysis from VOSviewer, authors' elaboration (ag. = agricultural; env. = environmental; sd = sustainable development).

In order to understand the interlinkage of climate change, food security and health, it is crucial to distinguish between identified clusters as well as to understand the connection among them.

3.1. Cluster 1: Climate Change and Food Security

Cluster 1 is the largest one, containing the two key concepts of climate change and food security. The size of the corresponding nodes was already anticipated before the analysis since keywords related to the two concepts form two major sections in the utilized search string. Looking further into the literature connected to this cluster, the closeness of both terms can also be explained by the great number of overview articles researching the relationship between climate change and food security with a broad view. With around 1500 citations, the work of Wheeler and Braun [23] is one of the most prominent within the field. The authors state that food prices may rise due to climate change, with even minor effects having a great impact, for example, through the destruction of crops caused by flooding [23]. Therefore, not only the food availability can be endangered through climate change impacts, but also economic accessibility may be at risk with rising prices. Additionally, extreme weather events can affect water availability, which is necessary for the essential hydration of the human body as well as for boiling certain foods [23]. Extreme weather events also pose a risk to the food supply chain, impeding food transportation, especially in rural areas [24], hence affecting the dimension of food accessibility. Climate change effects on food security may also cause dietary changes and a rising prevalence of diseases such as norovirus, salmonellosis or campylobacteriosis [24–26].

Another keyword that emerges in this cluster is COVID-19, which at first glance may seem unrelated, but the pandemic can be utilized as a predictor of future challenges and demonstrate the extent of social inequalities. In the United States of America (USA), women have been more affected by economic shocks than men, with even higher estimates for black and Hispanic women, illustrating the intersectionality of vulnerabilities. Having less income can result in altered food purchases, with less nutritional food or food in general. However, in the recent research findings of Belsey-Priebe et al. [27], it has been posed that climate change is also expected to have similar effects on food availability and accessibility as COVID-19.

In addition, fisheries are important for food security, especially in coastal countries or river deltas, and are also a source of income [28,29]. Fish provides proteins and fatty acids, which are essential components of a nutritious diet, and it is relevant, especially in Africa and Asia. For instance, in Ghana, up to 60% of the population's protein is consumed through fish, and with the prediction that climate change will affect fish biomass in the future, this will directly contribute to malnutrition [28]. In Lake Kariba, Zimbabwe, over half of the fishers (62%) reported fewer fish catches, with 78% stating that this decrease is causing food insecurity in their household [30]. Similar reports are available from around the globe, demonstrating that food security in countries relying on fisheries is being greatly affected.

Increasing temperatures and declining precipitation will lead to a decrease in some crops and an increase in others. Furthermore, in order to adapt to the changing climate conditions, farmers might harvest in areas that were previously conserved, contributing to land use changes, which could exacerbate climate change further [31]. Haque and Khan [32] estimated that a one-degree increase in temperature will lead to a crop yield decrease of 7–25% in Saudi Arabia, while others estimate a reduction in crop yield by up to 50% by 2050 [33].

Smallholder farmers often do not possess a great number of resources, relying on more basic agricultural forms, such as rainfed agriculture, which will be greatly affected by precipitation changes [34]. Hence, smallholders show a greater vulnerability to climate change than big farms [35,36]. Moreover, smallholder farmers who farm self-sufficiently have a greater risk of being food insecure due to the loss of income in addition to the loss of their grown food [33]. On the one hand, their vulnerability poses a risk to food security in developing countries. On the other hand, their social capital and knowledge could greatly support sustainable adaptation strategies [37].

Various studies also named education as an influencing factor that correlates positively with the application of climate change measures [31,38–40]. By analyzing exactly this factor, Bezner Kerr et al. [39] evaluated an educational programme for smallholder farmers. Their results show that farmers included in this programme were interested in the topics, such as agroecology, and wanted to apply this knowledge. However, they also reported difficulties, including those relating to language or cultural differences.

Difficulties in adaptation can also be found when moving on to another keyword within cluster 1, adaptative management. Wheeler and Brown [23] advocate for a "climate-smart food system that addresses climate change on all dimensions of food security". Others recommend a variety of adaptation measures, such as surveillance systems, risk assessments, early warning systems, or communicative measures to educate the public about the effects [26] or plead for the consideration of gender differences through a gender-sensitive adaptation approach in policy, as well as stakeholder engagement and social inclusion [41,42]. Other scholars recommend a focus on GHGs, like reducing methane and black carbon. According to them, reducing these two pollutants could lead to an estimated increase in crop yields by 135 metric tons by 2030 [43]. Since climate change, food security and health are global topics, equal global collaboration is important when tackling these issues [44].

One point of discussion in adaptative management is the search for synergies: the identification of adaptive measures that can simultaneously mitigate climate change [41]. The vast amount of these measures that acknowledge synergies can be found in the category of nature-based solutions [45].

An example of the absence of such synergies can be observed in barley production in the United Kingdom (UK), which is a supply used for the feed of livestock. Land-based climate change mitigation, such as conservation, can decrease agricultural land use, resulting in lower crop yields [46]. Similarly, land-based climate change mitigation in the UK is estimated to reduce the barley yield significantly, altering the UK's exportation of this good. This could not exclusively affect the UK's economy but also impact developing nations who likewise depend on this good for animal feed through a rise in prices [47]. A major issue to name here is the field of biofuel since it is a renewable energy source but does, in turn, require land to produce feedstock, withdrawing this needed land for use in food production [46,48]. This topic will be further explored in the corresponding chapter concerning cluster 3.

To conclude, cluster 1 represents an overview of the interlinkage between climate change and food security, while most of the aspects named within this cluster receive a more exhaustive analysis in the remaining clusters. Health, in turn, is not as pronounced in this cluster, although it has a close link to the corresponding cluster 3. Moreover, in the interlinkage of climate change and health, the direct effects are often in focus due to the easier access in terms of analysis, as mentioned previously [23,41]. More indirect impacts, like the pathway through climate change-induced food insecurity, are featured less.

3.2. Cluster 2: Agriculture

Cluster 2 is focused on the agricultural perspective in relation to the interlinkage of climate change, food security and health. In this cluster, crop and food production are pronounced keywords with bigger nodes. As described previously, this can be explained by the great amount of literature that is focused on the dimension of food availability. Furthermore, some of the researched crops can also be found in the cluster, such as maize, wheat and rice. The focus of climate change research in relation to food production and crops has often concerned precipitation changes, temperature or GHG-like carbon dioxide emissions, corresponding to the keywords that appear in cluster 2. Additionally, this explains the overlapping with cluster 4, which focuses on environmental aspects.

For instance, Tian et al. [49] studied the consequences of climate change, such as extreme weather events and O_3 (Tropospheric ozone is a GHG), on crops in China from 1981 to 2010. Their results show an estimated crop loss of 55 million tons annually, summing up to around 1.595 billion tons of loss in total for the analyzed 29 years. Equally, rice production in Asian deltas is vulnerable to a decrease in crop yield [50]. Rising temperatures can lead to a higher rate of salinization and water scarcity, affecting water-intensive crops such as rice. Since rice represents a major carb source for a lot of nations, this could have serious implications for human nutrition [50]. Remembering briefly the studies in cluster 1 [31–33], which also show a trend for reduced crop yields in the future, this is not the case for every crop, and how a crop will be affected by climate change varies between regions and types of crops [51,52]. Hence, the estimation of how climate change will affect food production and crop yields is difficult since it includes many parameters, and the results from one crop are often not transferable to other regions. In view of this, scholars are pleading for more interdisciplinary modelling that includes many parameters [51,53]. A more precise view of the impacts can support the creation of demand-orientated adaptation strategies and policy measures [51].

An issue from the agricultural perspective is the usage of fertilizer. Fertilizer is utilized to nourish plants; however, with the aim of compensating for the negative consequences of climate change, over-usage might not have a significant effect on the yield and result in adverse environmental effects (such as affected land ecosystems that lead to heightened vulnerability to climatic changes), contributing to climate change. Although this can also happen with organic fertilizers, the impacts are more hazardous with chemical ones. Moreover, as a short-term solution, chemical input can result in chemical contamination [54]. For instance, overfertilization can be observed in China; however, a reduction of around 30% would still lead to a sufficient crop yield but with a great reduction in GHG emissions [55]. Furthermore, the overuse of fertilizer in agriculture is equally mirrored in the advancing crossing of the planetary boundary of biochemical flows [56].

Cluster 2 also shows linkages with nodes thematizing adaptation from other clusters, relating to the agricultural adaptation strategies that can be used in the future. Diversifying crops and the usage of orphan crops (Orphan crops are those that are underutilized and not exported or imported as much as major crops (maize, wheat, . . .)) are some of the frequently discussed solutions [57]. For example, using rice sub-species such as japonica rice instead of indica would result in less GHG emissions and higher crop yields, according to the authors [57]. Particularly, nations that depend highly on rice as a carb source could apply similar measures [57]. Considering this, a lot of research has focused on major crops such as rice, wheat and maize, which is beneficial in terms of knowledge generation for adaptation. However, said focus can lead to a high dependence on major crops and the neglect of others, such as orphan crops, like amaranth, which hold potential for climate change adaptation and enhancing food security [58]. This crop has a relatively high resistance to droughts, making it particularly suitable for regions with a high risk for droughts, it can grow under a wide variety of conditions, and it is already used in diets around the globe, such as its use in crackers or chapattis in Himalayan populations. Moreover, it is nutrient-dense, bioactive and contains a lot of unsaturated fats and fibre, all suitable for a healthy diet. It can also be used as livestock feed. Nevertheless, more research is needed to analyze the practical implications of amaranth utilization [58].

More adaptation strategies can be found linked to the agricultural management node. Organic farming is another possible pathway to more sustainable farming. However, as Wekeza et al. [59] show in their systematic research from southern Africa, the often-lower crop yields do not favour the application of this measure [59]. Nonetheless, organic farming approaches should not be neglected in the search for adaptation strategies. Agricultural intensification, for example, is usually perceived as a short-term solution for food security with long-term effects on the environment, such as increased chemical input in order to gain a higher crop yield. However, a more organic approach to intensification through the use of organic fertilizers, intensive care for the plants, and planting seeds further apart, could enhance the output greatly without adverse impacts on the environment since the increased output refers to labour or capital. The mentioned methods have been estimated to boost the crop yield by up to 180%, depending on the crop type. Agrochemicals as an adaptation in agricultural management might seem contrary, given the adverse effects chemical fertilizers can have on the environment. Despite this, further investigation and innovation in agrochemicals could form a pathway if they only enhance the resistance of plants against fungi or bacteria [60]. As mentioned previously, the above-described adaptation strategies could be greatly supported by smallholder farmers applying such strategies, which again connects clusters 1 and 2 [37].

3.3. Cluster 3: Human Health and Nutrition

The third cluster focuses on health and human nutrition perspectives within the interlinkage of climate change, food security and health. Here, keywords such as nutrition, malnutrition, health, public health, health status and diet can be found. It is estimated that currently, around 210 million children are suffering from stunting and wasting, and around 790 million people do not meet their daily requirements in terms of energy intake [61].

The increase in CO_2 tends to decrease protein, iron and zinc in crops, potentially causing nutrient deficiencies and contributing to malnutrition in the population [62,63]. Ebi and Ziska [63] estimate that these increased CO_2 levels might lead to 125.8 additional disability-adjusted life-years globally. Besides nutrient deficiencies caused by environmental stressors on crops, dietary changes can adversely affect health. It is estimated that there will be an additional half a million deaths in 2050 due to dietary changes caused by climate change [24]. Climate change may restrict dietary diversity since crops and other food sources will be lost, become more expensive, or be constrained in terms availability, leading to a higher consumption of highly processed, cheaper foods that are more easily accessible. This is a serious risk for the exacerbation of the triple burden of malnutrition: malnutrition, undernutrition and overnutrition, potentially causing obesity [64].

Dietary changes induced by climate change can also be observed in indigenous populations that mostly rely on locally harvested food [65,66]. For instance, the Inuit in the western Canadian Arctic are an indigenous population. Depending on the community, they traditionally consume wild animals, such as caribous or different types of fish [67]. These animals contain essential nutrients for a healthy diet, like zinc, protein, vitamin D or omega-3 fatty acids. Climate change can cause an alteration of animal populations, leading to a decrease, which is also the case for the wild animals that the Inuit diet commonly includes [67]. Concludingly, important nutrient sources might disappear in the future for the Inuit communities, and in light of the cultural importance of food, it is difficult to replace these sources. This could also result in a loss of traditional knowledge, damaging the traditional food systems [67,68]. Communities with a high dependence on solely one species for their diet especially have a high risk of developing nutrient deficiencies [67].

Returning to malnutrition, an intergenerational cycle can be observed, meaning that malnutrition will be inherited from the parents to their children, to their grandchildren and so on [24]. Maternal malnutrition contributes to this and has also been estimated to be exacerbated by climate-change-induced food insecurity [69]. The consequences of climate change could make breaking this cycle more difficult due to added stressors. Particularly, malnutrition in children can have long-term effects on their health, causing stunting or wasting in children. Teams of authors have shown examples from the African continent where heat increases are associated with a rise in malnutrition and the risk of wasting in children [70,71]. Moreover, Grace et al. [72] conducted a multi-level regression model in sub-Saharan Africa to examine the correlations between child malnutrition and climate change. They have found that a combination of increased temperatures and lessened rainfall correlates with stunting in children.

There are also more indirect pathways in cluster 3 through which climate change can affect food security and human health. For instance, climate change can generate conflicts, i.e., due to limited resources, and conflicts heighten the risk of food insecurity, which can induce poor health [26,61,73]. This can lead to a vicious cycle of adverse effects from climate change, food insecurity and poor health on vulnerable population groups [74]. Rural-to-urban migration movement due to the climate change effects of food insecurity can lead to an increased population in slums, where unhygienic conditions can alter food utilization and therefore further exacerbate food security [26]. Conflict or other extreme weather events can increase food prices or provoke a loss of GDP, leading to food insecurity. Additionally, missing labour force or altered international trade due to climate change effects or the described conflict scenarios may affect food production, as was observed with food shortages during the COVID-19 pandemic or with the Ukraine conflict [75]. Suffering from food insecurity may reduce nutrient intake, causing malnutrition, poor general health and a higher risk of being affected by diseases or developing them. Moreover, a negatively altered food quality can elevate the prevalence of food diseases, such as salmonellosis [24,64,75].

Similar to cluster 1, the keyword of adaptation is represented with a large node. However, in contrast, the discussed adaptation in this cluster refers more to the behavioural aspects of climate change adaptation. For instance, policies that support a more plant-based diet could support climate change mitigation, food security and health risks. Firstly, it could mitigate climate change since livestock production is often coupled with high GHG emissions. Secondly, decreased GHG emissions could lessen environmental stressors, protecting food security. Lastly, a higher consumption of plant-based food could improve the population's cardiovascular health [76].

The keyword biofuel forms a transition to cluster 4, environment and the other adaptative-related keyword nodes. Biofuel is increasingly used as a renewable energy source, requiring raw materials to be produced. Raw materials can be palm, soybean, or sunflower, which need land to grow [77]. The land used for these materials could otherwise be utilized to grow crops for food consumption. While biofuel can support climate change mitigation, discussions exist about their potential downsides, like deforestation for land use, setting free GHGs, or issues concerning the high usage of water. On the other hand, biofuel can also increase food prices [77]. Therefore, biofuel is an example that can show the tension between climate change mitigation and food security.

3.4. Cluster 4: Environment

Cluster 4 concerns the environmental perspectives on the interlinkage of climate change, food security and health. The focus within this cluster lies on soil health. Soil is important for food security since healthy soil contributes to thriving crops and prevents soil degradation. To undermine its importance, the FAO estimates that around 95% of food is produced in soil [78]. It provides the necessary minerals for plant growth, such as nitrogen or phosphorus, but also some minerals essential to a nutritious diet, such as iron, magnesium, or calcium.

Increasing temperatures can lead to less water availability in the soil. This is a risk factor for soil erosion, endangering the soil fertility of plants [79,80]. Additionally, climate change can influence the nutrients available in the soil and the nutrient cycle. Precipitation changes due to climate change, such as droughts or floods, can cause nutrient leaching [79]. The nutrients in the soil leach into the ground and become unavailable in terms of uptake by plants, resulting in lower nutrient content in the end product. Fewer nutrients available might motivate a higher usage of fertilizer, which again adversely affects climate change [79]. On the other hand, depending on the species and climatic events, the rise in CO_2 and temperature can boost the nutrients in the soil. For instance, a temperature increase might indirectly result in higher phosphorus availability in the soil [79]. Nonetheless, a boost in terms of nutrients does not equal uptake by the plant, and a greater availability of phosphorus could lead to the unwanted spread of fast-growing plants [79]. While some crop yields may increase due to climate change and altered nutrients in the soil, decreased crop yields will dominate this development after 2030 [79,80].

Another beneficial factor of healthy soil is carbon sequestration, meaning, among other things, that the soil holds carbon dioxide, which could otherwise be in the atmosphere and damage the environment. Researchers estimate that soil holds the most carbon on planet Earth [79]. Hence, soils are an important carbon sink. Soil degradation and the loss of organic matter lead to the release of the carbon stored in the soil, transferring it into the atmosphere where it contributes to the GHG effect, accelerating climate change. Different agricultural management, including farming techniques, such as low-carbon agriculture, can enhance carbon sequestration in the soil [81].

Looking further into agricultural management, land use and agricultural land are other keywords that can be found within this cluster. Land use change can either contribute to climate change with the deforestation of areas or be a consequence of climate change due to the previously described soil erosion. The latter is a risk to food security since the land on which crops can be harvested will be reduced [82]. With proper land use management, climate change can be mitigated and food security enhanced. However, land use management is influenced by a variety of factors, such as geopolitical issues. This underscores the importance of finding adaptation measures that do not solely consider the factors but also their interlinkage in order to create synergies [83,84].

Besides crops, livestock will be greatly affected by climate change due to extreme weather events or more indirect pathways, such as bacteria and parasites, as further explained in cluster 5 [85]. Looking at the direct consequences, the occurrence of extreme weather events can, at worst, wipe out livestock. However, increasing temperatures also might decrease animal weight, resulting in less production. Heightened prices for animal feed due to droughts and fewer crop yields can equally affect livestock production adversely [86]. Livestock is particularly important for smallholder farmers in developing countries as a food and income source where the amount of soil suitable for crops is greatly limited [86]. The loss of livestock as a food source and rising prices due to less availability could lead to protein deficiencies when considering that animal products make up a third of the protein consumed in the population.

3.5. Cluster 5: Quality of Food

The last and smallest cluster is cluster 5. This cluster is different from the others since it does not have a clear assemblage. The four keywords it contains (food quality, food safety, climate and disasters) spread into the middle of the figure and are closely intertwined with all the other clusters. This could be caused by possible alterations in terms of food quality in any stages included in the other four clusters.

Mycotoxins are a commonly mentioned problem in the literature [87–90]. They are produced by mould fungi and, depending on the dose and type of mycotoxin, they can be toxic to humans and animals. Bridging this with the previous chapter, soil erosion and the loss of microbial biodiversity in the soil can not only lead to a loss of soil minerals but also makes the plant more vulnerable to mycotoxins and other diseases [89]. The possible consequences of mycotoxins can be chronic diseases, different types of cancer and, ultimately, death due to their carcinogenic and mutagenic properties [89]. If the crop is already exposed to unsuitable environmental conditions, mycotoxins can thrive more [91].

Apart from livestock being affected by contaminated feed, climate change events might also result in the faster spread of diseases. For instance, this can be due to the animals being closer together indoors with extreme weather events, where the spread of disease is quicker, or by floods. This might not only alter the species used as livestock (species with higher heat resistance will be favoured), but it could also contribute to antimicrobial resistance, posing a threat to human health. Three pathogens have been associated with increased prevalence relating to rising global temperatures [89].

The spread of pathogens is another issue within the topic of food quality. Like crops and mycotoxins, the effect of climate change does equally depend upon the pathogen and its optimums. Nonetheless, with increasing temperatures and altered precipitation, an increase in water- and foodborne diseases is anticipated since the endemic area, growth, survival and transmission of pathogens are influenced by environmental conditions [89,91]. Along with other factors, such as tourism, climate change is a major inducing factor in relation to harmful algal blooms, posing a risk to food security provided through the fishery sector and human health. Hence, both food- and waterborne diseases lead to increased morbidity and mortality.

Moreover, vectors such as flies will be increased, which can transmit pathogens onto food, and the melting ice in glaciers or the Arctic could result in the occurrence of bacteria. These were previously frozen and now might pose new risks, for example, in the fishery sector [89]. Salinization or increased UV radiation can alter the toxicity of organic chemicals, being lethal for some marine animals, thus putting pressure on fisheries. In addition to that, salinization and temperature have been shown to increase the uptake of metals with toxic properties, such as mercury, in marine animals [89].

Meanwhile, other elements, such as polycyclic aromatic hydrocarbons (polycyclic aromatic hydrocarbons are set free during forest fires or in the production of fossil fuels), can have an altered, broader distribution with changing climate. They are distributed over air, dust and soil and can be transferred onto animals or vegetables where they are a concern in terms of food safety. Polycyclic aromatic hydrocarbons have carcinogenic and mutagenic properties [92]. Focusing solely on the environmental conditions caused by climate change, more food might be spoiled due to heat or humidity. Both can favour the growth of bacteria and, under certain temperatures, this can even affect dry or heat-processed food, leading to an altered taste that might result in food waste [89].

To protect crops from climate change effects and increase their yield, pesticides are utilized. However, pesticides can contaminate the crop and leave traces, possibly being later ingested by humans. They could also affect the agricultural workers directly through the respiratory system or skin contact and pollution in the environment [92,93]. The changing climate conditions might alter the behaviour of pesticides on the appliance; thus, there is a greater risk of misuse [91]. Moreover, as previously mentioned, the use of fertilizer and pesticides not only poses a risk to human health but can also have adverse environmental effects that contribute to climate change [93]. Furthermore, when low-quality crops are not consumed due to health risks and are wasted, they still contribute to food waste in the food production stage and reduce the availability of food, contributing to food insecurity [89]. To that end, if crop productivity is lessened and insufficient food is available, either due to land use conflicts or climatic events such as floods, it could lead to compensation in relation to the consumption of lower-quality crops that contain trace amounts of pesticides or are contaminated with mycotoxins [92].

3.6. Theoretical Framework

The clusters described provide an overview of the current research status in relation to climate change, food security and human health. Through this analysis, it can be observed that while climate change effects in the future will increase in frequency and intensity, both food security and health are already being affected. For instance, knowledge obtained from the COVID-19 pandemic foreshadow how crises affect food security. Various case studies of effected regions or populations show vulnerabilities, such as those in relation to smallholder farmers and regions in the Global South. Those who already exhibit high vulnerability to climate change are likely to be vulnerable to food insecurity. Cluster 1 has several health implications, such as an anticipated increase in gender-based violence due to the potential food insecurity crisis. Furthermore, overall hunger and poverty rates are expected to increase, putting a strain on individuals' health and reducing their resources to cope with health stressors. A more specific health implication is mentioned in the fisheries section, where fish availability is estimated to decline. Here, populations with high fish consumption will lose an important source of protein and fatty acids. Proteins are essential for bone health as well as cell regeneration, and fatty acids support overall health and resilience to diseases [94,95]. Moreover, the stress of food insecurity leads to adverse mental health outcomes, especially when smallholder farmers are at risk due to the loss of their harvests.

From the agricultural perspective in cluster 2, there is evidence of how food availability is already and will be affected by altered crop yields. Major carb sources, such as rice, are expected to decline. While this is not the case for every crop due to different optima, the adverse consequences are estimated to make up a majority after 2030. Additionally, the focus of research has been on major and annual crops, yet there is a knowledge gap in terms of other types of crops. To counteract lowered harvests, the misuse and abuse of fertilizer is a great risk because it could further contribute to climate change, and the pollution it causes in air or water runoff threatens health. Substitution with other crops or orphan crops may be a possible solution. Thus, the most prominent health issue within cluster 2 included malnutrition stemming from harvest reductions. The diseases associated with it increase depending on the nutrients involved. For example, iron deficiency risks further increasing the already high rates of anaemia [96].

Since cluster 3 focuses on the health perspective, it was expected that most information about health implications could be derived. A decrease in nutrients in crops is expected. While this also depends on the type of crop, the loss of nutrients is still estimated to result in nutrient deficiencies and disability-adjusted life years. Moreover, dietary changes resulting from altered food availability, as described in indigenous case studies, contribute to the triple burden of malnutrition. Diseases associated with malnutrition, as well as NCDs, are estimated to increase in the future. Additionally, if food-insecure populations cannot meet their dietary requirements, they are exposed to a higher vulnerability to infectious diseases. In children, stunting, wasting and other developmental impairments are expected to increase, as shown in the present study. Food insecurity causing a heightened risk of malnutrition can also be induced by climate change-induced conflicts that limit resources, such as missing labour force, migration, altered food production, or GDP loss. To that end, the circumstances of conflict and food insecurity also impact mental health, which, in turn, can influence physical health.

Another factor endangering food security is declining soil health. With rising sea levels that push the salinization of the soil forward, soil degradation is also progressing. Reduced nutrient content in plants poses another risk in terms of increased nutrient deficiencies in the human population. Moreover, the loss of carbon sequestration and land-use change may further exacerbate this by contributing to climate change. Another health consequence within cluster 4 is the loss of livestock due to climate change, which could result in the previously described malnutrition and health issues associated with it.

Food quality, which is distributed throughout the bibliometric figure, affects all stages of food production. This can occur in the pre-harvest stage due to the misuse of fertilizer, crops that are contaminated with mycotoxins, or in fisheries through contamination with harmful algae that enter the food chain, affecting humans consuming seafood. However, heated, canned, or dry food post-harvest can still be affected by high temperatures during heat waves, exhibiting risks in terms of bacterial growth. The most common health consequences are food- and waterborne diseases, such as salmonellosis, campylobacteriosis, vibriosis and different types of shellfish poisoning. While some of these are diarrheal infections that can be treated with bed rest and medication, in a low-resource context where they are expected to increase the most, a diarrheal infection can be lethal.

In all clusters, to a certain extent, to mitigate the effects of climate change on food security affecting human health, the literature features various recommendations on how adaptation could be conducted. This can be observed in the graph since either cluster contains a keyword related to adaptation or different keywords from the clusters connected to them (i.e., cluster 2 crop connected to adaptive management from cluster 1). While the adaptation recommendations vary depending on the perspective of each cluster, there is broad consensus on several measures: education for food producers (particularly smallholder farmers and fisheries), a more plant-based diet within the population, and sustainable measures that consider the synergies and the interdisciplinary spectra within the interlinkage of climate change, food security and human health. While the dimension of food availability has been the main focus point in scholarly literature, bibliometric analysis shows that climate change has various implications for all dimensions of food security. Looking back at the theoretical framework, information from the bibliometric analysis enables the building of a base for practical implications, as represented in Figure 3.

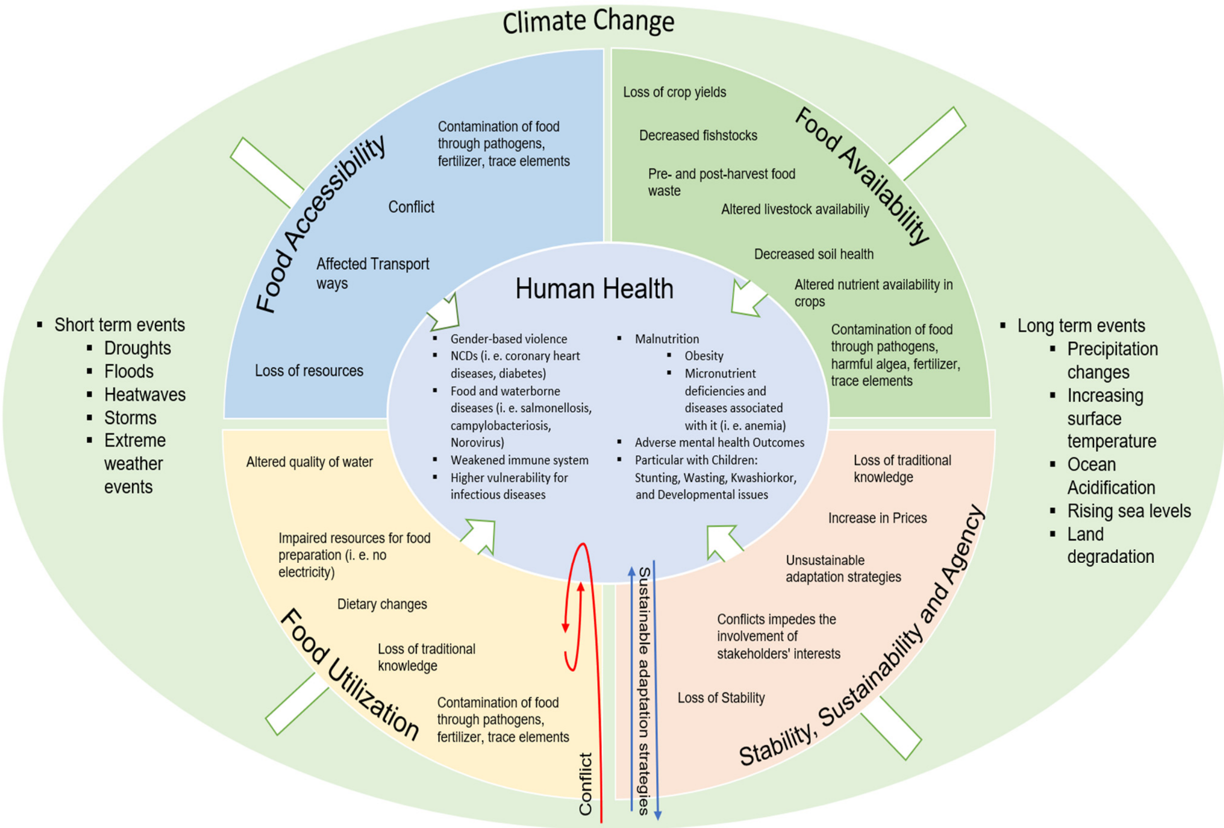

Figure 3. Theoretical framework with practical information from the bibliometric analysis and authors' elaboration. In light of the first objective of the paper, namely, how are the three key concepts linked to each other, the graph shows the different variables that form and influence the interlinkage. For example, it can be observed that climate change affects food security through various complex pathways, from more direct ones, such as extreme weather events that destroy crops pre-harvest, to more indirect ones that threaten food safety due to pathogens thriving with rising temperatures and entering the food chain in marine animals.

The consequences of climate change are displayed in two different categories: short- and long-term. These factors adversely affect food security dimensions, causing different consequences that were previously described through the bibliometric analysis. Food availability decreases, whether in relation to crop yields, fish or livestock. Moreover, post- and pre-harvest losses due to extreme weather events, declining soil health and altered nutrient content in crops and the contamination of food, are consequences that affect the dimension of food availability. Regarding food accessibility, if food is scarce and expensive, lower-quality food might still be consumed by people with low resources, leading to potential health issues. Additionally, conflict, destroyed transport methods or the loss of resources through climate change events can lead to altered food access for people. For instance, if a conflict results in price increases, food may become less accessible to people with less income. However, if the transport methods are destroyed by flooding, some food might not be accessible in the affected region. For food utilization, the altered quality of water due to floods and the possible contamination of food can hinder hygienic preparation. Other extreme weather events may damage the resources required for food preparation, such as the electricity network. Dietary changes and the loss of traditional knowledge induced by climate change, limit food choices and also negatively affect food utilization.

For stability, sustainability and agency in the face of the unexpectedness of climate change events that alter other food security dimensions, there is a loss of stability and an expected increase in prices. Moreover, conflicts caused by climate change can impede the involvement of stakeholders' interests, which would also affect the involvement of consumers' opinions in relation to food policy. Unsustainable adaptation strategies, increased prices and the loss of traditional knowledge equally negatively affect the three dimensions.

In the inner circle, the health implications for the population are characterized by less dietary intake, leading to fatigue or decreased nutrient intake that leads to malnutrition and poses a risk factor for disease. In general, the triple burden of malnutrition will increase in the future if no action is taken since the consumption of cheaper, highly processed foods might result in the heightened prevalence of NCDs. Furthermore, other adverse health outcomes are listed, such as gender-based violence, food and waterborne diseases, weakened immune systems and increased stunting in children.

However, there are more hidden pathways in the linkages, such as climate change causing conflicts that influence population health, decreasing the available workforce or GDP, leading to an increase in food prices, which will then again increase food insecurity and then affects health. This is illustrated by the red arrow, which, depending on the exact scenario, can affect all the dimensions. Lastly, the sustainable adaptation strategies are marked with blue arrows since they can create synergies between the three concepts. This also includes all dimensions.

4. Conclusions

This work contributes to a better understanding of the interlinkage between climate change, food security and human health by summarizing the status quo of the scholarly literature. The analysis conducted reveals various pathways through which the three key concepts influence each other, pointing to the indirect pathways through mediators, that is, bacteria hazardous to health set free through climate change-induced ice melting affecting the fish stock, etc. The bibliometric analysis applied has highlighted the different research directions in this area that have prevailed to date: the overarching perspective on food security and climate change, agriculture, the environment, human health and nutrition and food quality perspectives. This knowledge was then sorted in terms of its implications for the different dimensions of food security, which have been illustrated in the framework (Figure 3). Moreover, the analysis has shown that while the food availability dimension has received much attention so far, more research is needed on other dimensions, as well as on different types of food sources. Each cluster that was analyzed has different focus points, but they are connected to each other in various ways, often through the identification of adaptation measures. Hence, human health, when defined as a sustainable state (as described by Last [18]) that thrives in balance with the environment and enables humans to live actively in a community, is endangered by climate change-induced food insecurity through various pathways.

In terms of practical implications, the work has shown the importance of adaptation measures that find synergies and interdisciplinary work toward sustainable. The involvement of all stakeholders is necessary to conduct sustainable changes in food systems. Many starting points for adaptation have been identified, whether it is on the individual side through dietary changes towards a more climate-friendly, plant-based diet or on the more advanced side through plant breeding for more resilient crops. For the education of health professionals about the health impacts of climate change, the work shows that the indirect impacts of climate change are just as likely to greatly influence population health and, therefore, form important research areas. Implementing climate change mitigation measures alone may compromise food security or vice versa, which in turn negatively impacts human health. Moreover, in education about climate change and the health nexus, food security is an important mediator that needs to be addressed.

However, while bibliometric analysis is replicable and is based on a great number of pieces of scholarly literature, there are limitations that should be kept in mind when interpreting the results. Since bibliometric analysis uses the academic literature, it is likewise affected by publication bias [97] or missing data from the most vulnerable and hard-to-reach populations.

Finally, this work demonstrated that the interlinkage between climate change, food security, and health would have a great impact on society in the future. Future studies should consider the many variables that influence this interlinkage, and while increasing the knowledge of existing ones, also consider the ones that have not been discovered yet, to enhance future policy making. With climate change comes the heightened risk of exacerbating existing vulnerabilities and inequalities as well as food security and health issues, and sustainable adaptation and mitigation are essential measures to protect the most vulnerable from the impacts of climate change and to build a sustainable, prosperous future for all.

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