agronomy

Review

Climate Change and Citriculture: A Bibliometric Analysis

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Abstract: Citrus are the most produced fruits worldwide. It is expected that these crops will be severely affected by climate change. However, the literature lacks works that attempt to understand the influence of climate change on citrus. For this reason, a bibliometric analysis was conducted on climate change and citrus to investigate its development and current trends in this research domain. The main trends, keywords, and their relations were identified. The period from 1992 to 2022 was analyzed, resulting in 178 documents in the Scopus database. The most significant publishers' countries were also the largest citrus producers in the world besides being G7 members. Three main research areas were identified: modeling, socio-political issues, and plant physiology. A tendency to change interest from modeling and risk analysis to physiology and stress studies was observed. Additionally, some of the most cited papers observed the positive impacts of climate change on certain citrus crops. Despite the multidisciplinary publications, two main gaps were identified: (i) the lack of investigations with combined stresses (abiotic and biotic) instead of isolated studies, and (ii) the lack of studies of predictive models for citrus production in different conditions and climate change scenarios. Finally, there was a tendency toward studying water use and irrigation alternatives due to water scarcity and management solutions to improve the production system's resilience, considering the potential impacts of climate change.

Keywords: global warming; citrus; agrometeorology; literature review; bibliometry

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1. Introduction

In this digital era, scientific knowledge is produced quickly and widely diffused through the internet. Every day, new data are being published on all domains of knowledge [1]. With this considerable amount of information being disseminated, the understanding of the status of a research topic is not only vital but also a research challenge.

Defining the state-of-the-art in a specific domain demands significant time and effort and is prohibitive if carried out manually in several research domains. This scenario demands specific techniques and tools that can be used to acquire and process information from a vast number of scientific studies. One method that directly addresses this problem is bibliometric analysis. This quantitative analysis allows for identifying relevant keywords, authors, sources, references, trends, gaps, and tendencies of a specific research field [2].

Additional justifications for using the bibliometric method are: identifying emerging trends and research area performance; identifying authors' and countries' collaboration patterns; better understanding the research areas involved with a specific topic; and exploring the evolution of a topic throughout time [3]. Paraphrasing Donthu et al. [3], the bibliometric analysis is "useful for deciphering and mapping the cumulative scientific knowledge and evolutionary nuances of well-established fields by making sense of large volumes of unstructured data in rigorous ways".

Nevertheless, this is not a recent tool. Its first use record is from the 1950s [2]. However, it has recently increased its importance with the emergence of scientific databases, such as Scopus and Web of Science, and software packages and tools, such as VOSviewer [4] and biblioshiny [5].

As the most produced fruits in the world, citrus is a group of fruits present in 140 countries, with a global production reaching over 2 billion boxes of 40.8 kilos [6]. Similar to most crops, citrus have their cycle highly affected by environmental characteristics, and climate change can directly influence fruit yield.

This paper applied a bibliometric analysis to better understand the connection between climate change and citrus research. The main goal of this study was to identify the current status of this research field through a chronological analysis of keywords and citations, identifying gaps and tendencies. The results of this study can be used to help with decision-making related to future scientific studies in the domain.

This paper is organized into the following sections: Section 2 describes the materials and methods used in the bibliometric analysis, Section 3 presents the results obtained and discusses their most significant impacts, and Section 4 concludes this work, presenting perspectives for the future and its main limitations. Section 1.1 describes the main aspects of climate change and its potential impacts on agriculture and farm production.

1.1. Climate Change and Its Impacts in Agriculture

Anthropogenic activities have been changing the climate in the last decades, especially since the beginning of industrialization. The last report of the Intergovernmental Panel on Climate Change (IPCC) [7] presented alarming data on the alterations in the global weather, observing the fastest temperature increase in fifty years considering the last two millennials.

Greenhouse gas concentrations, such as CO_2, CH_4, and N_2O, are at their peak considering the last eight hundred thousand years, and extreme heat, cold events, and intense precipitation have increased, both in terms of frequency and impact. The IPCC report [7] also suggested dramatic possible future scenarios (Coupled Model Intercomparison Project—CMIP6), showing the urgency of ambitious actions against climate change.

Temperature increase, high CO_2 concentration, and variation in water dynamics alter the rates of chemical reactions of all living organisms, especially plants. Additionally, extreme weather events resulting from climate change, such as heat waves, intense precipitation, and droughts, among others, directly affect global agriculture [8]. Thus, in addition to being essential for several supply chains, agricultural activities may present an increasing economic risk in some areas of the world. This requires adopting new management strategies that aim to overcome the obstacles posed by climate change while optimizing the use of natural resources.

Citrus is one of the most popular fruit crops globally, grown in 140 countries [6]. Among these countries, China is the largest producer, with Brazil and India as the second and the third largest producers, respectively [9]. The 2019/20 world harvest reached almost 150 million tons, and half of it was composed of oranges, followed by tangerines/mandarins, lemons/limes, and grapefruits [6].

A critical aspect of those fruits is their excellent nutritional characteristics. In addition to their taste and aroma, citrus fruits have a high content of vitamins, especially vitamin C, a potent antioxidant [10]. They also have flavonoids, carotenoids, and limonoids in their composition, which may help to address various chronic diseases [10].

Climate change is expected to impact citrus yields, fruit quality, and logistics and distribution activities. This has already been observed in several other crops, such as soybean, corn, cotton, sunflower, wheat, barley, sugarcane, and cassava [11].

In this context, improving the quality and accuracy of yield predictions is critical for decision-making. For this reason, several works in the literature aim to improve predictions of the primary inputs of productivity-related models, such as air temperature, gas concentration, and water availability in different areas [12–14].

The effects of increasing temperature will vary according to the phenological stage of the crop and may anticipate or even shorten events that require degree-day accumulation [15]. In addition, higher temperatures will increase water demand and CO_2 consumption due to the acceleration of enzyme activity, impacting various processes, such as photosynthesis [14].

According to Vu [16], scenarios with high CO_2 concentration will lead to better photosynthesis, water use efficiency, growth. This may have a direct impact on fruit quality. Furthermore, as plants with ample carbon storage in their biomass and soil, citrus orchards may be a viable option in agroforestry systems that aim for climate change mitigation with CO_2 sequestration [17]. However, the nutrients requirement will also increase to achieve such a metabolic level, demanding citrus genotypes with a higher nutrient absorption efficiency [14].

Lastly, climate change may lead to significant variability in precipitation and, consequently, water availability. This may result in intense droughts and floods [7] in different parts of the world. Both temperature and CO_2 concentration increases will influence water requirements [12], and its supply will depend on water availability. A high-temperature scenario is expected to increase plants' evapotranspiration, resulting in higher irrigation needs and better water use efficiency [18].

However, to better understand the potential impacts of climate change on the citrus supply chains, it is essential to describe the main links involved in those chains. The following section explores this aspect, describing a generic supply chain that can be applied to different citrus fruits.

1.2. The Different Citrus Supply Chains

When studying the impacts of climate change on agri-food chains, it is common to focus only on farm production. However, this approach ignores the potential impacts on other links in the supply chain, which are essential to generate demand and distributing the products. The supply chain in citriculture comprises of processes and institutions that provide inputs for production, farms, and the processing and distributing stages [19].

A generic citrus supply chain can be described by four main stages, as illustrated in Figure 1 and described by [20,21]: (i) the farm inputs, such as implements and fertilizers, are produced and distributed by cooperatives or industries; (ii) the farms use the inputs in their production processes, resulting in the harvesting and transportation of the fruits out of the farms; (iii) several companies are involved in packaging, processing, storing, and transporting the products; and (iv) the final products are distributed to the end consumer, via distribution centers, retailers, wholesalers, or open markets. For an in-depth description of each link in the citrus supply chains, we refer the reader to the works of Bitzer and Bijman [21], Raimondo et al. [22] and, Liao et al. [23].

In addition to losses due to biotic and abiotic challenges during fruit development, operational errors and waste are present along all the links of the citrus supply chain, notably in the logistics and transportation of the fruits. Liao et al. [23] identified the logistics stage as one of the many waste points in a citrus supply chain.

According to [23], after harvest, the citrus fruits are usually packaged for distribution (to be transported for open markets, distribution centers, or industries) using plastic boxes that are never returned for recycling. The authors then proposed turning the linear process of the supply chain into a cycle, recycling the boxes used. This would reduce the amount of waste considerably while also improving the supply chain's resilience. In general, proposed changes in supply chains aim to reduce waste and improve different aspects of the processes in the supply chain links.

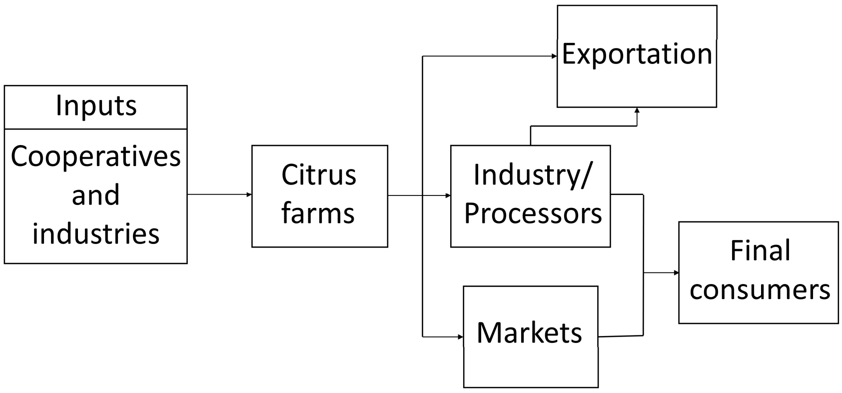

Figure 1. Citrus supply chain. Each box corresponds to a stage composed of operations, inputs, production outputs and residues.

Therefore, climate change will affect the whole citrus supply chain, from farm production to end consumer distribution. However, it is also interesting to note that climate change and the citrus supply chains are mutually influencing each other since: (i) waste and management errors in supply chain processes can increase greenhouse gases emission and pollution [24], and (ii) the environmental alterations caused by climate change increase supply chain challenges, as observed by Godde et al. [25]. Lastly, despite the specificity of each context, there is a tendency to worsen current risks in places with higher temperatures and limited socio-economic resources, such as developing countries.

As was observed, citrus supply chains are complex, and analyzing the potential impacts of climate change in those chains is very challenging. The contexts of the different producing regions are diverse, the concentration of the different players in the supply chain links change between countries, and several climate change scenarios must be evaluated to improve decision-making and planning.

Additionally, there is a vast amount of literature on the impacts of climate change on citriculture, focusing on different aspects such as farm production and product distribution, considering different fruits and operational processes. We use the bibliometric analysis methodology to address the problem of extracting valuable insights from this considerable amount of research. The following section illustrates the use of this methodology on different agri-food supply chains.

1.3. Bibliometric Analysis Applied to Agri-Food Supply Chains

The study of agri-food supply chains has gained increased attention in the last 20 years due to their approach to integrating environmental, economic, and sociological knowledge domains and their relationships [19]. The broader look provided by a supply chain can facilitate agricultural system analysis and management of errors and waste compared to the traditional analysis considering only the farm link of the supply chain.

When adding the generated residues and possible losses to every supply chain link, reverse logistics aspects can be raised as relevant challenges. This allows for changing the supply chain from a linear process to a cycle that recycles several materials and reduces waste [23]. Additionally, this evaluation becomes even more important in a scenario of limited resources and increased potential impacts of extreme weather events.

Understanding the current status of the research on the potential impacts of climate change on citrus supply chains is crucial in the face of the high number of publications and information. The bibliometric analysis methodology allows knowledge extraction from a considerable amount of information quickly. It can be used to investigate a vast amount of documents using quantitative methods [3]. As an example, a simple search in the Scopus database for the word 'supply chain' in the titles, abstracts, and keywords of papers in the knowledge domain of Agricultural and Biological Sciences, and Environmental Science results in 30.020 documents. The traditional systematic literature analysis is prohibitive when considering such an amount of documents.

Bibliometric analysis has been mainly used in the field of the agri-food supply chain, including, among others: several areas, such as supply chain management [26], supply chain risk management [22,24,27], green supply chain [19] and crops supply chain [21,23]. The following section describes the main inputs used for the analysis and its main steps.

2. Materials and Methods

This section describes the main materials and methods used in this research. It is composed of the following sections: Section 2.1 describes the process of data collection and processing, following state-of-the-art works in bibliometric analysis such as the one by [28] Section 2.2 describes the knowledge extraction and analysis processes, including the tools used and their main hyperparameters, to allow for better replicability.

2.1. Data Collection

To analyze the state of the art of the scientific literature and the current research trends related to climate change and citrus, we initially verified the total number of publications related to this field in the Scopus database. A simple search of the strings "climate change" and "citrus" or "citriculture" was used.

Next, based on a thorough analysis of the most cited literature reviews found in this search [12,14,28], the following terms were selected for our search: "climate change" and "citrus". The search criteria considered the presence of those terms in the papers' titles, abstracts, or keywords. The period of analysis was from 1992 to 2022 due to the increasing amount of research on climate change starting that year. Only after 1992, significantly relevant papers were found.

This search resulted in 339 documents. Next, a two-step selection was conducted: first, the titles of all papers were analyzed, considering their relevance for the analysis of the potential interaction between climate change and citrus plants or supply chains. All the irrelevant work was eliminated. Several works from other fields of study were eliminated, mainly from: anthropology, medicine, mathematics, civil engineering, and marine biology. Next, the final step was to conduct a similar analysis considering the remaining papers' abstracts. The following section describes how the knowledge was extracted from the final dataset generated.

2.2. Knowledge Extraction and Analysis

The VOSviewer software [4] was used to identify and analyze the relationship between countries, co-citations, and terms of the resulting documents. According to Van Eck and Waltman [4] and Van Eck and Waltman [29], the Vosviewer software is a tool for identifying, implementing and visualizing bibliometric networks using a clustering algorithm developed by the authors. Two main visualizations were provided: (i) the clusters found and the relations between those clusters, and (ii) a term map, which illustrates the most important terms for each cluster and their relations. In this work, we have used the second visualization, as it allows for a better exploration of the most important keywords and their relations, better describing the contents of the works analyzed.

As described by Van Eck and Waltman [29], it is important to observe that the clustering algorithm used by the Vosviewer software estimates how each publication is related to each other based on direct citations. Considering direct citations reduces several problems compared to using single-word relations [29]. Additionally, it is essential to observe that the publications are assigned to one cluster only. Therefore, there were no overlapping between clusters, and all publications had one cluster assigned to them [29]. For a further description of the Vosviewer software and the hyperparameters of the clustering algorithm, we referred the reader to the works by Van Eck and Waltman [4] and Van Eck and Waltman [29].

The final documents dataset was inserted in the VOSviewer software. After an initial analysis of the keywords contained in that dataset, several irrelevant words and synonyms were identified. Therefore, we have created two lists: (i) contained irrelevant words for the research, such as animal, article, control, level, need, order, and paper, and (ii) encompassed synonyms such as climate change, global climate change, and climate change scenario. Both lists were used as filters to improve the results of the clustering algorithm.

After an extensive hyperparameters analysis of the minimum co-occurrence for each term to be considered was conducted, considering from 3 to 15 times. The best performance was obtained with a minimum co-occurrence of 9 times. This was evaluated based on the resulting clustering, considering the keywords and the clusters formed. A minimum co-occurrence lower than 9 generated too many clusters with seemingly irrelevant terms, whereas a value higher than 9 resulted in too few clusters with only obvious terms (and no possibility of gathering additional insights).

The bibliometrix R package [5] complemented the bibliometric analysis through the 'biblioshiny' web-based interface. The same processing methodology (eliminating irrelevant terms and concatenating synonyms) was used. A threshold of ten words was selected to implement the descriptive analysis tools, such as publication and citation per country graphics and tree map. Selecting additional keywords did not improve the quality of the analysis. We chose to analyze the trending papers by citations in total and per year according to Van Nunen et al. [30].

The collaboration map was created using the value of one as the minimum edge and the network map by removing isolated nodes. A repulsion force of 0.1 was selected, as this was the default for the tool. After an extensive analysis of different values for the word minimum frequency and the number of words per year, we have decided to use a minimum frequency of five and two words per year to analyze the trending keywords. Finally, the thematic map was created using two cutting points: 2010 and 2017, due to the presence of works containing a considerable number of citations in those years. The Walktrap clustering algorithm was used, as it is the default used in the tool. The following section describes the results obtained and discusses their main impact, both on the research community, practitioners, and other decision-makers.

3. Results and Discussion

This section describes and discusses the main results obtained in this research. It is composed of the following sections: Section 3.1 describes the results of the exploratory data analysis, presenting the total number of publications, distributions per country, collaborations per country, the main works and authors, and the main keywords identified, Section 3.2 presents a keyword co-occurrence analysis, illustrated by two network maps, and Section 3.3 contains a thematic analysis, considering different time slices and theme groupings.

3.1. Exploratory Data Analysis

In total, 178 documents related to "citrus" and "climate change" were identified. These documents were classified into 133 journal papers, 18 book chapters, 16 reviews, 10 conference papers, and 1 book. The documents had an average citation of 12.87 per year, with an annual growth rate of 11.53%.

Between 1992 and 2018, two years presented peaks in the number of published papers: 2010 and 2013. These are mainly related to an increase in the importance of climate change research at the beginning of the 2010s. However, after 2019, the total number of documents published per year increased exponentially, reaching 38 documents in 2021 and 28 documents only in one semester in 2022 (Figure 2).

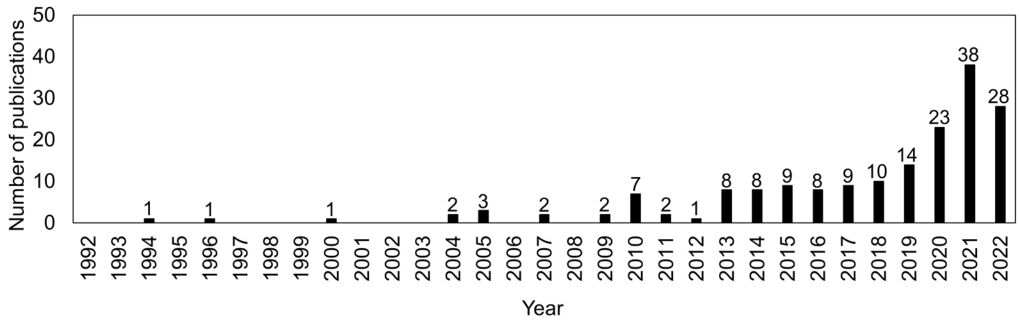

Figure 2. Number of publications in the final dataset between 1992 and June of 2022.

Some of the main factors that may help explain those results are: (i) new reports and scientific research on climate change, such as the ones by Ryan [31] and Aish et al. [32], (ii) increased importance of applying machine learning and artificial intelligence models and techniques to better understand and predict the impact of climate change in different domains, as explored in the work by [33], and (iii) the availability of cheaper hardware and software for evaluating and predicting the climate and its impacts on agriculture. For an in-depth analysis of the use of machine learning models for addressing climate change aspects, we refer the reader to the extensive and in-depth work of [33].

Figure 3 indicates the origins of the publications by the total number of documents (Figure 3a,c) and citations (Figure 3b,d). Interestingly, both metrics emphasize the largest citrus-producing countries in the world. These are, in decrescent order: China, Brazil, India, Mexico, USA, Spain, Egypt, Nigeria, Iran, and Turkey [6]. Economic development seems connected to each country's academic and scientific efforts since the top five are developed countries (Spain, USA, China, and Italy).

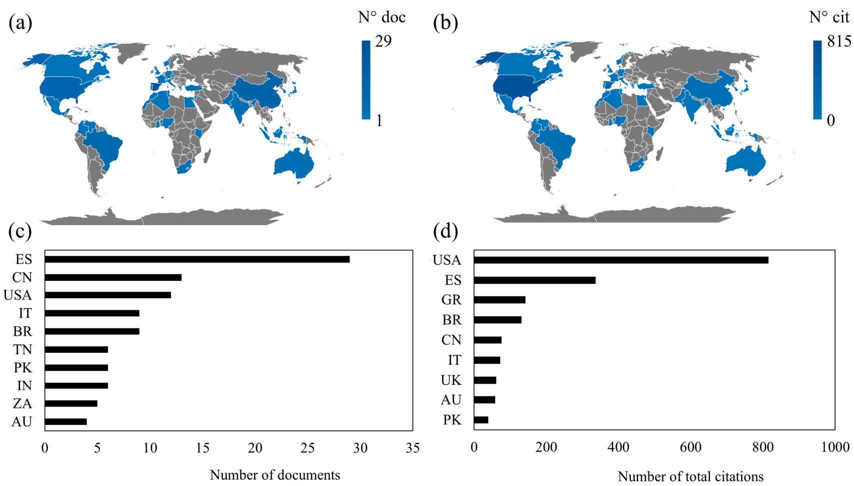

Figure 3. (**a**) Map of the total number of documents per country. (**b**) Map of the total number of citations per country (**c**) Total number of documents per country. (**d**) Total number of citations per country.

The relation between the economic level of a country and its scientific production is a relevant theme in literature, being explored in several works. Laverde-Rojas and Correa [34] and, Gantman [35] have observed that the size of an economy has a significant positive effect on its scientific output. However, other variables influence a country's scientific production besides the economic factor, such as political and cultural diversity [35]. For example, the country's primary language can affect the number of papers published in English. In the case of non-English speaking countries, a considerable amount of relevant research may be produced in its native language [35].

Figure 4 illustrates the research collaboration networks between countries. In this map, thicker lines connecting countries correspond to stronger collaboration. The USA presented stronger connections with other countries in South America, Africa, Europe, and Asia. Brazil also had many collaborations, although most of these partnerships are composed of only one published paper (represented by the thin red lines). Lastly, it was also observed that the strongest connection between two countries is between China and Pakistan, with 4 documents published together.

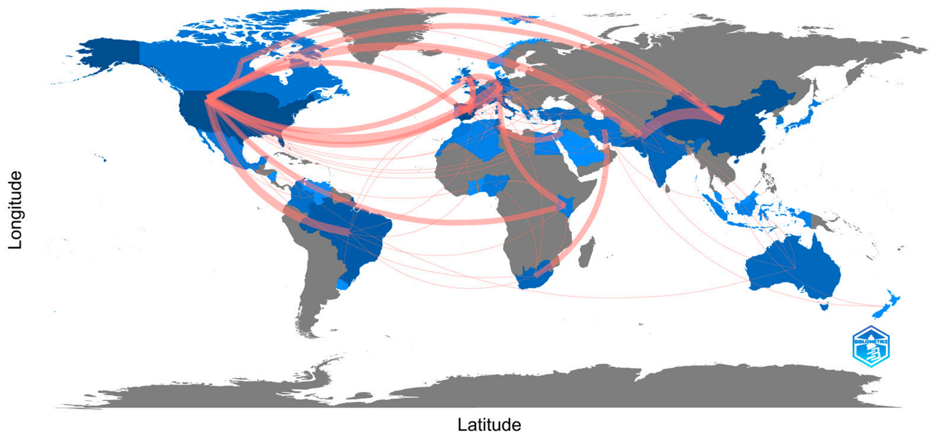

Figure 4. Collaboration between countries as co-authorship in papers. The intensity of the blue color indicates higher number of collaborations.

Brazil and China correspond to the world's greatest citrus producers, which probably justifies their relevance in collaborations with other countries. It is also interesting to observe a need for more collaboration between those countries, as this could allow for significant advances that directly impact worldwide citrus production.

Despite the observed connections between countries, most co-authorships are restricted to authors from the same country, as illustrated in the collaboration clusters presented in Figure 5. For example, the light green cluster comprises of authors from South Korea, the dark blue cluster belongs to Spain authors, and the dark pink cluster contains authors from Pakistan. Therefore, most of the authors' relations occur in the same country, and sometimes in the same institution.

Figure 5. Network map of authors' collaborations.

Increased collaboration between authors from different countries, climates, and contexts could allow for significant advances in analyzing the impacts of climate change on citrus supply chains. This would allow for viewpoints on better monitoring and addressing climate change issues, improving the resilience of the different citrus supply chains. This collaboration could improve research quality, increasing the studies' visibility, creating more extensive scientific networks, and allowing for better knowledge transference [36].

In addition to analyzing the collaborations between authors and countries, it is vital to identify the most relevant papers in the final dataset. Table 1 illustrates the five most cited papers, and Table 2 contains the five most cited papers, considering the number of citations per year. The most important paper considering both metrics is a review of the environmental changes' effects on the roots' development and longevity of citrus plants [37]. The authors pointed out relevant information about how CO_2 increases can improve root life through N concentration in the tissues and root maintenance through a reduction in respiration rates.

In the fourth most cited paper, CO_2 elevation is also emphasized. Similarly, this work also found positive results with CO_2 concentration increase leading to increased biomass accumulation and productivity [38]. These two papers aimed to elucidate some questions about the potential effects of climate change on plant development since the environmental variation caused by climate change can influence each step of crop growth and all the interactions with other organisms.

The second most cited paper also reviews climate change consequences in agriculture, but with a different objective. It focused on saline water use since a probable consequence of global warming is a reduction in both water availability and water quality. According to Paranychianakis and Chartzoulakis [39], salinity's main effect on plant physiology is diffusional and can vary in different regions. With the rise in CO_2 concentration, some citrus plants that are more tolerant to salinity will be favored. This is the case of Sunki mandarin, Cleopatra mandarin, and Rangpur lime.

The third most cited paper was also a literature review, which discussed how variations in temperature and humidity could influence plant diseases and their control [40]. The authors present results from weather alterations in several diseases for different crops. They have observed that, depending on the context and phenological stage, these can be positive (for example, reducing pathogen development) or harmful (for example, amplifying pathogen expansion). The fifth most cited paper was an experimental study in which the authors presented irrigation methods and the water quality effects on the microbial community of a grapefruit orchard, also focusing on understanding how climate change may transform water use [41].

Table 1. Most cited papers in the final dataset.

Ranking	Authors	Title	Source	Year of Publication	Citations
1	Eissenstat et al. [37]	Building roots in a changing environment: Implications for root longevity	The New Phytologist	2000	622
2	Paranychianakis & Chartzoulakis [39]	Irrigation of Mediterranean crops with saline water: From physiology to management practices	Agriculture, ecosystems & environment	2005	123
3	Ghini, Bettiol & Hamada [40]	Diseases in tropical and plantation crops as affected by climate changes: Current knowledge and perspectives	Plant pathology	2011	96
4	Kimball et al. [38]	Seventeen years of carbon dioxide enrichment of sour orange trees: Final results	Global Change Biology	2007	61
5	Bastida et al. [41]	Combined effects of reduced irrigation and water quality on the soil microbial community of a citrus orchard under semi-arid conditions	Soil Biology and Biochemistry	2017	59

Table 2. Most cited papers in the final dataset, considering citations per year.

Ranking	Authors	Title	Source	Year of Publication	Citations per Year
1	Eissenstat et al. [37]	Building roots in a changing environment: Implications for root longevity	The New Phytologist	2000	28.3
2	Duan et al. [42]	Role of groundcover management in controlling soil erosion under extreme rainfall in citrus orchards of southern China	Journal of Hydrology	2020	15.0
3	Tschora & Cherubini [43]	Co-benefits and trade-offs of agroforestry for climate change mitigation and other sustainability goals in West Africa	Global Ecology and Conservation	2020	14.5
4	Shafqat et al. [44]	Heat shock protein and aquaporin expression enhance water conserving behavior of citrus under water deficits and high temperature conditions	Environmental and Experimental Botany	2021	14.0
5	Bastida et al. [41]	Combined effects of reduced irrigation and water quality on the soil microbial community of a citrus orchard under semi-arid conditions	Soil Biology and Biochemistry	2017	11.8

It is essential to observe that three recent papers published between 2020 and 2021 were among the most relevant papers in Table 2. Using different approaches, those studies aimed to find acceptable agricultural practices and processes to help mitigate the adverse effects of climate change, including extreme weather events, better water use, and heat-related impact. This denotes a trend towards more practical research, which can be directly applied to improve the resilience of fruit production.

The second most relevant paper in Table 2 was an experimental study on the impact of extreme rainfall and the use of groundcovers, focusing on evaluating the impacts of erosion processes in a citrus orchard [42]. The third most relevant work investigated the effect of shaded plants on tree crops in an agroforestry system, which could result in increased food security and sustainability with high carbon sequestration potential [43]. The fourth most relevant paper was also an experimental study on different citrus species and their tolerance to heat-related impacts and water deficit [44].

Next, an analysis of the most important keywords was conducted, considering the most used keywords in the title and abstracts of the analyzed documents. One relevant aspect of this analysis is the number of times a term must occur to be considered relevant. Several values were evaluated, and we concluded that only terms that occurred at least nine times within the documents were considered for better visualization and analysis. Reducing the number of necessary occurrences of each term led to a considerable increase in the number of terms without relevant impacts in gathering additional insights.

Figure 6 illustrates the word cloud generated with the most important terms identified. The size of each word represents its importance on the dataset. The terms observed in this figure corroborate the analysis presented in this work. The most frequent terms, besides "citrus" and "climate change" were: "photosynthesis", "yield" and "water stress". There was also a group of key terms connected to abiotic stresses: "adaptation", "cold stress", "drought", "water use efficiency", and "mitigation".

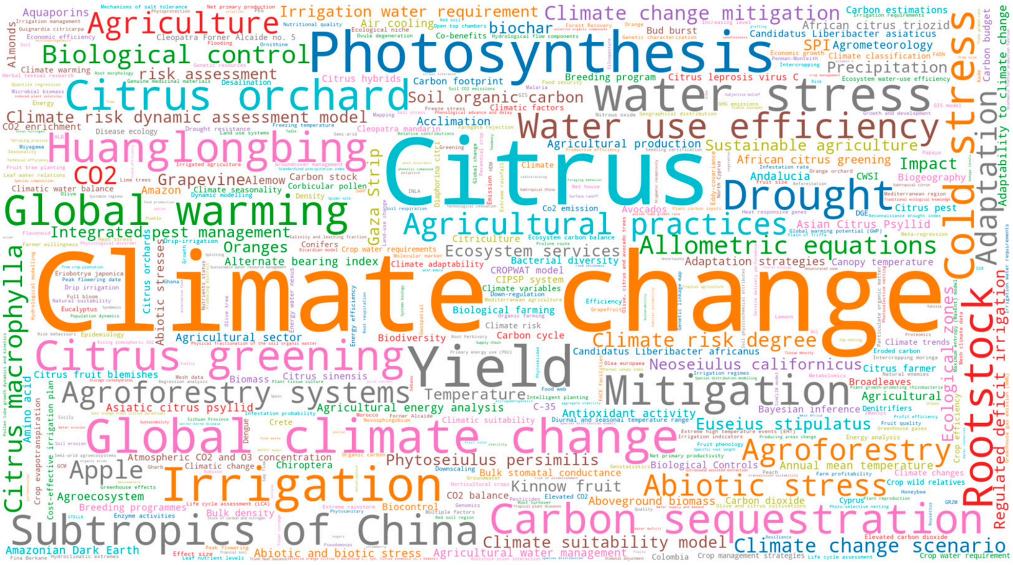

Figure 6. Word cloud of keywords.

Additionally, it is possible to notice a group of terms related to biotic stresses: "huanglongbing", "citrus greening", "*Candidatus liberibacter asiaticus*", and "biological control". Those keywords illustrate the importance of both biotic and abiotic stresses and their relations with climate change and citrus production.

Figure 7 contains a tree map diagram designed to explore those terms' distribution better. The number contained with each term corresponds to the number of times that term was used. In addition to "climate change" and "citrus", terms such as "irrigation" and "rainfall" were very relevant.

Figure 7. Tree map diagram of keywords.

Figure 8 contains an analysis of the most relevant trending keywords over time, also referred to as trending topic analysis. It shows that terms such as "water stress", "yield", and "abiotic stress" presented an increase in frequency and relevance over the analyzed years. Considering the past analyses, it is possible to notice that the most relevant publications (illustrated in Tables 1 and 2) and the most important terms (illustrated in Figures 6–8) are related to stresses of different types and origins, with a highlight on the impacts of water management and water availability in climate change scenarios.

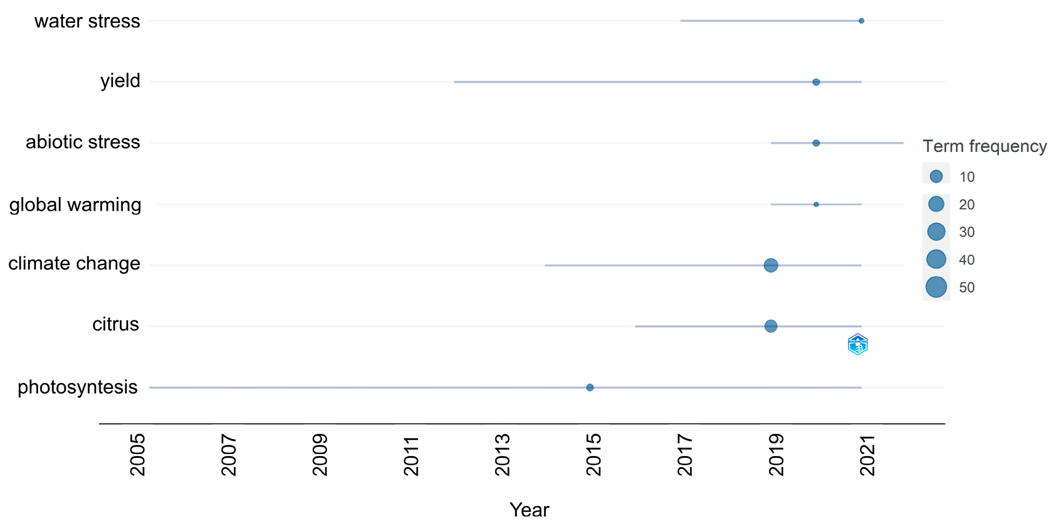

Figure 8. Trend keywords analysis.

The high frequency of studies on abiotic stress is due to its direct relation with the impacts of climate change, such as temperature elevation, water scarcity, and extreme events occurrence [7], and the consequent impact of those occurrences on yield. According to several authors, climate change will intensify irrigation requirements in citrus orchards [12,18,32,45–47]. Therefore, a critical trend in the literature is identifying, proposing, and evaluating different irrigation strategies that may increase sustainability and profitability in those scenarios [48,49].

In addition to abiotic stresses, the interaction of those physical variables (temperature, humidity, and water availability) with pathogens or pests can modulate their development. In this case, more aggressive pathotypes adapted to higher temperatures can emerge [50], increasing the need to develop processes and products for reducing their population and impact on yield.

Papers about the huanglongbing disease (HLB) and its vector's behavior, along with abiotic stresses, are the majority of biotic stress studies found in this work due to its significant risk to the economy and food security [51]. Additionally, temperature increases may negatively affect the vector since this condition can alter citrus plant flushing, reducing the feed period for the vector (*Diaphorina citri* K.) [52]. Similarly, drought negatively affects the vector population, consequently reducing the occurrence of HLB disease [53]. The following section will further the analysis of the most important keywords by developing two network maps of keyword" co-occurrence.

3.2. Keyword Co-Occurrence Analysis

In order to complement and deepen the analysis of titles and abstracts' keywords, a network map with keywords relations was created using 73 words and 2471 links (Figure 9). The size of each point illustrates the frequency with which a keyword was used. The network map in Figure 9 presents three clusters. The clusters represent keywords that tend to appear together in the papers on the final dataset. The names for each cluster were given according to an interpretation of the knowledge domains that contained most of its keywords.

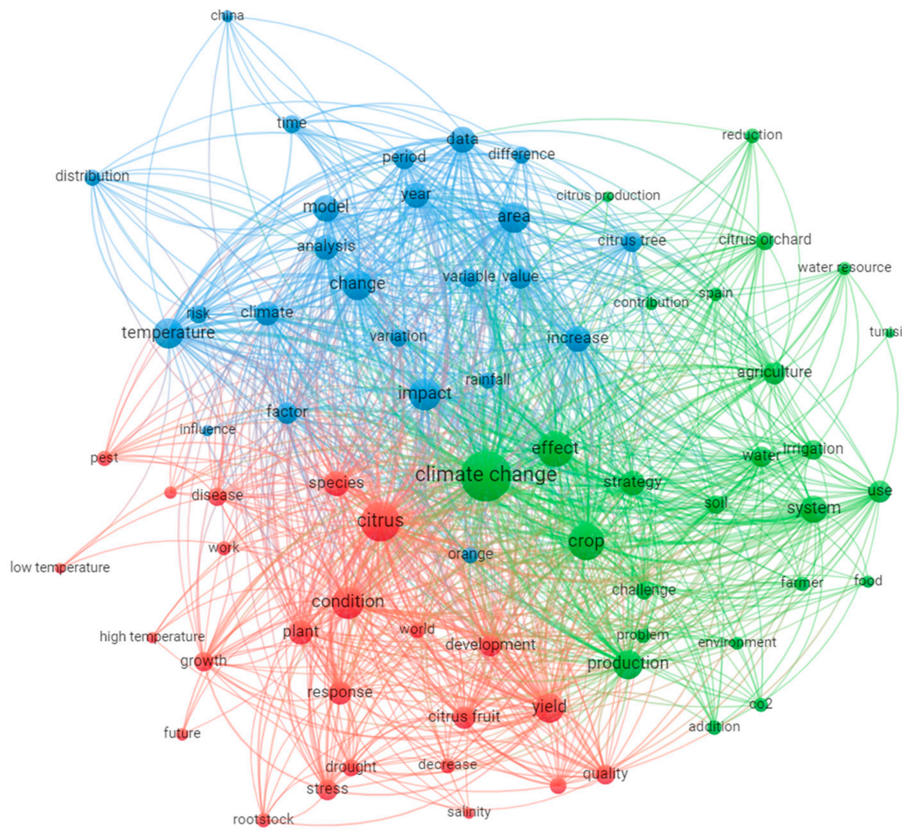

Figure 9. Network map based on co-occurrence of terms on titles and abstracts of the final dataset. Each color represents a cluster.

The first cluster (red) was named "Citrus physiology and potential impacts of climate change." It is composed of terms related to a plant's development and the stresses faced during its growth and production, such as "growth", "species", "citrus fruit", "rootstock", "stress", "salinity", "drought", "low temperature", "high temperature", "disease" and "pest".

Most papers in this cluster tended to evaluate or explore how climate change could affect abiotic and biotic stresses and their relations with citrus crops. The papers that studied abiotic stresses focused on three main variables: water (extreme rainfalls and deficit —[12,39,41], temperature (heat and cold—[54–56], and CO_2 concentration—[16,38]). Except for one paper that simultaneously analyzed the combination of heat and drought [57], all other articles studied the isolated abiotic stresses.

However, it is critical to consider that the current scenario in citrus farms combines all stresses simultaneously, demanding analyses considering their interrelations. For example, in a drought scenario, which leads to stomatal closure and gas diffusion reduction, the elevated CO_2 in the air may counterbalance this effect by increasing the photosynthesis substrate [12].

Nevertheless, water scarcity may intensify salinity, which can be highly damaging to the plant and the production, regardless of CO_2 air concentration [39]. In this example, the most accurate analysis would then consider the effects of all those aspects: climate, extreme weather events, water availability, and salinity. The papers that studied biotic stresses analyzed the effect of changing those three variables on pests [31,52,53] and pathogen [40] dynamics.

Much effort was put throughout the years into comprehending the relationship between climatic variables and pests/pathogens to predict crop yield. As HBL disease is one of the most critical issues in citrus production [58], some papers analyzed, how climate change may influence the vector (psyllid—*Diaphorina citri*) behavior and cycle, analyzing its expansion in different areas [52,53].

Martini and Stelinski [53] verified that water deficit might reduce the psyllid population. The increase in temperature might have a similar impact due to its effect on flushing, which will start earlier, and have a shorter duration [52]. Nevertheless, the authors also point out that increasing temperature might alter the suitability of some areas to the vector and the disease, leading to HBL challenges in currently non-infected areas.

The second cluster (blue), named "Climate change modeling and scenario analysis", presents keywords connected to: (i) climatic risk analysis, such as "increase", "impact", "factor", "influence"; (ii) variables involved in climate change, such as "temperature" and "rainfall"; and (iii) considering different time windows, such as "period", "time" and "year". The main goal of most works in this cluster was to predict behaviors and evaluate scenarios to provide tools and insights for improving decision-making.

Most of the articles focused on water use, because water availability is one of the biggest challenges related to climate change [7]. According to Martínez-Ferri et al. [45] and Aish et al. [32], in future scenarios (2050 and 2080), the evapotranspiration demand will increase for citrus plants. This will increase irrigation demand in different areas, requiring more precise use of this resource. The same scenario was observed by Pereira et al. [18], who also estimated the water productivity in current and future scenarios, with and without irrigation.

This cluster also encompasses research on the different regions' suitability for citrus considering several climate change scenarios and predictions [59]. In some cases, the authors observed an expansion of the suitable area for citrus production. However, more work is needed to understand better how citrus suitability for different regions may change over time.

The third and last cluster (green), defined as "Socio-political impacts of climate change", consists of key terms related to sociological and political issues regarding climate change and citriculture, such as "strategy", "farmer", "challenge", "problem", "production", "environment", and "effect". The focus of this cluster is to shed light on another essential aspect of climate change and agriculture: the farmers' perceptions, demands, and needs.

Some papers studied the advantages and possibilities of using agroforestry systems with citrus and other crops as restoration tools with high carbon sequestration and conservation potential [43,60]. Tschora and Cherubini [43] also stated the relevance of an agroforestry system in food security, since climate change can reduce food availability and access to the different agri-food chains.

A group of works analyzed how farmers evaluate and consider climate change effects on their production [61] and water use [62]. This is relevant, since their decisions are directly connected to the production systems and the use and availability of natural resources.

According to the authors, besides noticing the adverse effects of climate change on production or the crops' cycles, public policies and transparency still need to be improved, especially in water supply management [62]. These results point out the importance of the socio-political aspect of climate change and the necessity of extension activities to bring science to the field and improve the resilience of production systems. Such activities may be based on risk analysis for each local and demographic situation, as Iglesias et al. [63] studied for Spain.

Figure 10 illustrates a map of the terms' co-occurrence varying over time, enabling the visualization of trends. A shift in research focus was observed throughout the period. Initially, most works focused on temporal analysis and risks regarding farm production. Next, works began to focus on biotic and abiotic stresses and social challenges. This temporal analysis indicates how socio-political aspects grew in importance along with abiotic stress effects over time. One significant side effect of this evolution was the development of tools and analysis that may bring essential insights for planning and decision-making for different stakeholders, from farmers to industries, banks, and Government agencies. The following section further describes an analysis of the evolution of the different themes for the analyzed documents.

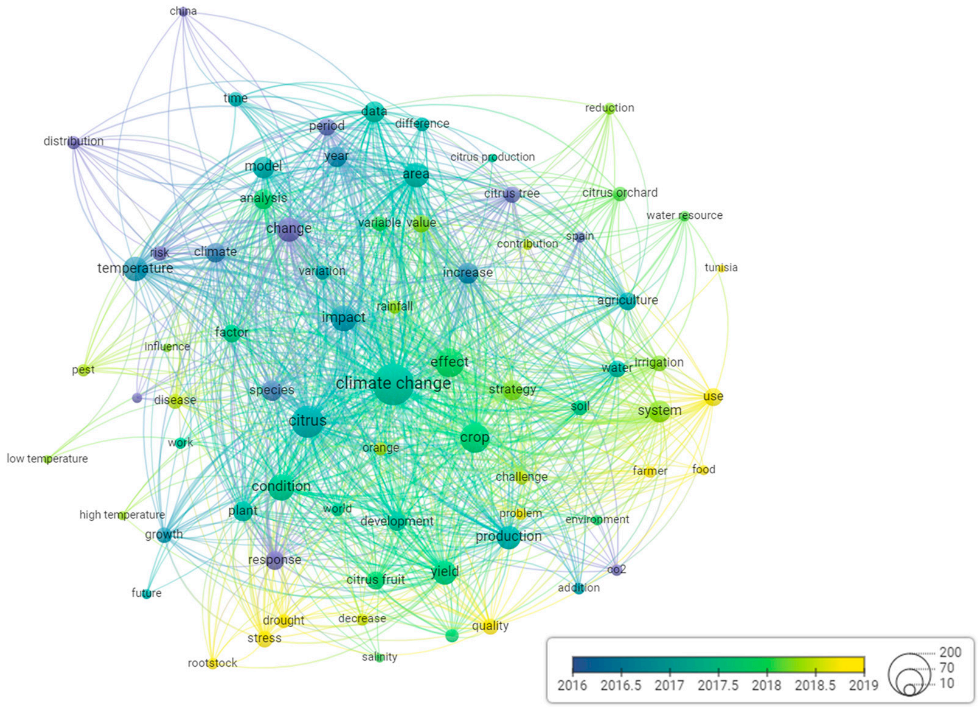

Figure 10. Network map based on co-occurrence of the terms presented on titles and abstracts of the final dataset along time.

3.3. Thematic Analysis

In Section 3.1, two years were identified as significant for research on climate change and citrus production: 2010 had the first peak, and 2018 began the exponential trend in the total number of papers published. Therefore, in this section, we will analyze the main themes of the documents published in three time slices: between 1991 and 2010 (initial period, first peak), between 2011 and 2017 (second period, continuous increase), and after 2018 (third period, exponential growing trend).

Figure 11 illustrates the result of the thematic analysis considering those three slices. The first time slice was composed of three main themes: "climate", "citrus", and "citrus sinensis", illustrating a focus on farm production.

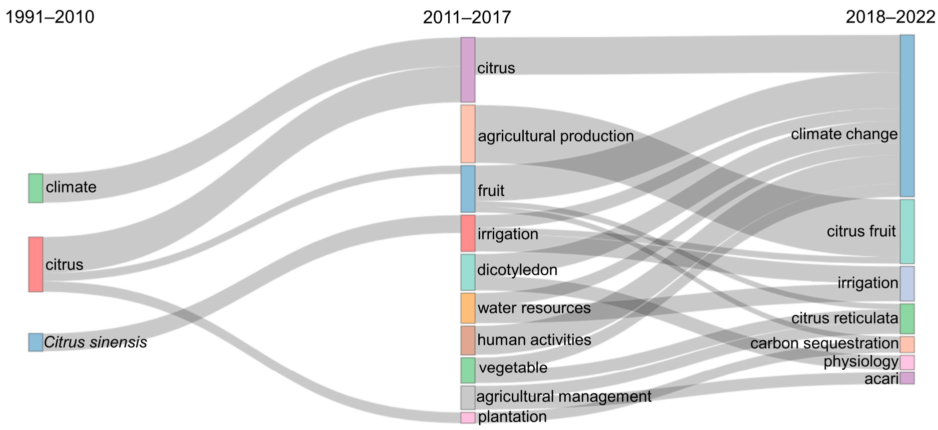

Figure 11. Thematic evolution map based on co-occurrence of the terms presented in authors' keywords. Each color indicates a cluster.

In the second time slice, those terms were broadened into four themes: "citrus", "fruit", "irrigation", and "plantation". In that time slice, six new themes emerged: "agricultural production", "dicotyledon", "water resources", "human activities", "vegetal", and "agricultural management". This may be related to the increased importance of professional management on farms, adopting irrigation practices, and better resource allocation.

Lastly, in the final analysis period, several themes were concatenated into "climate change", denoting the relevance of this term and its use in practically all research papers in the final dataset. Additionally, new themes appeared: "citrus fruit" (related mainly to the increased concern for product quality and not only quantity), "irrigation" (related to the effort to improve irrigation methods and processes), "citrus reticulata" (probably due to an increase in the importance of tangerines in the global market), "carbon sequestration" (due to an increased interest in using carbon sequestration strategies to reduce the impacts of climate change), "physiology" (related to an increasing need to evaluate how the plants may respond to the changes in temperature, water availability, soil salinity, among others), and "acari" (related to works trying to identify better how to deal with increased problems with pests and pathogens).

Overall, the thematic evolution map indicated the same behavior for keywords as the network map illustrated in Figure 10, with an increase in interest in themes regarding plant physiology and water use ("irrigation", "water resources", and "agricultural management") in the last period analyzed. The main keywords for those themes in each time slice is further analyzed in Figure 12 (1991 to 2010), Figure 13 (2011 to 2017), and Figure 14 (2017 to 2022).

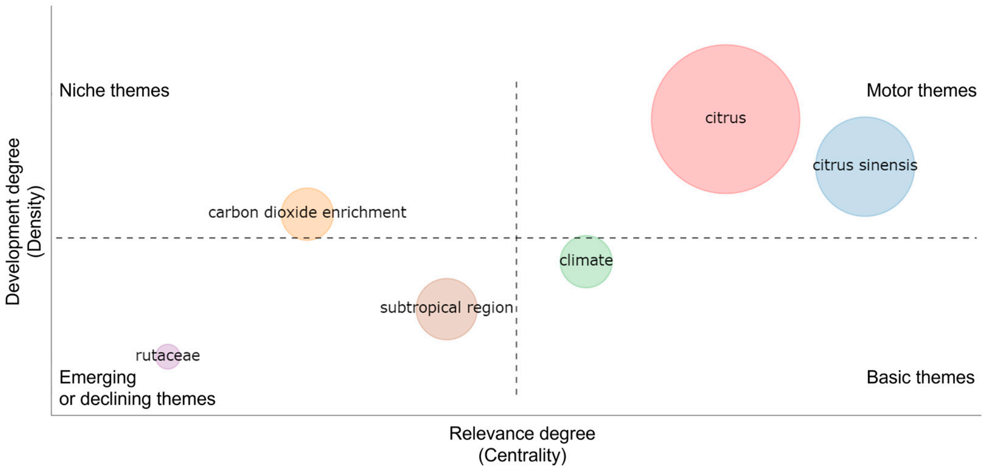

Figure 12. Time slice graphic from 1991 to 2010 from the thematic evolution map.

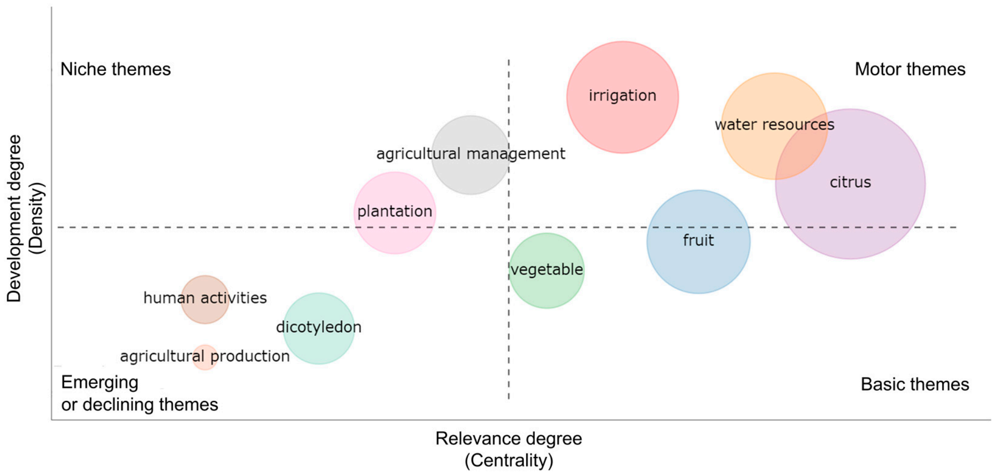

Figure 13. Time slice graphic from 2011 to 2017 from the thematic evolution map.

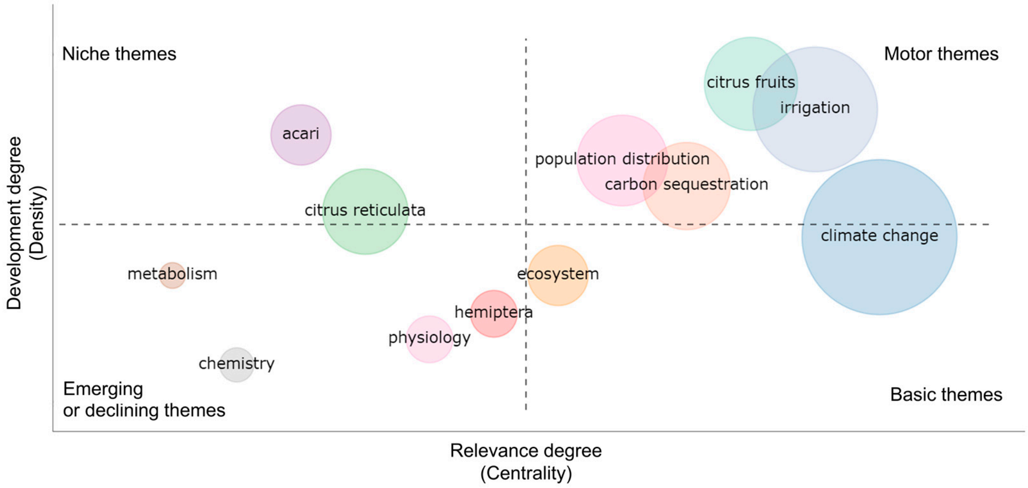

Figure 14. Time slice graphic from 2018 to 2022.

This analysis considers two main metrics: (i) centrality, which is related to the relevance of the specific term; and (ii) density, which is related to the level of development of the area. These form 4 categories: (i) niche themes (low centrality, high density), indicating themes that are important for a few specific, impactful works; (ii) emerging or declining themes (low centrality, low density), related to themes that are increasing or decreasing in terms of importance during the period; (iii) basic themes (high centrality, low density), which are themes that occur in almost all works analyzed; and (iv) motor themes (high centrality, high density), which are themes that are relevant and characterize most of the works analyzed.

Analyzing those four categories is critical because it allows the identification, for each time slice, of: the themes that are contained in all works (basic themes); the themes that are driving the research field (motor themes); the themes that are very important for specific works and areas (niche themes); and themes that may be decreasing or increasing in importance, depending on the context of the analysis (emerging or declining themes). For more details on using this tool, we refer the reader to the work by [5] and the biblioshiny package.

Figure 12 illustrates the results of the time slice thematic analysis from 1991 to 2010. "Climate" was the only basic theme that permeated all research in this period, denoting its importance in guiding research. The main motor themes were "citrus" and "*Citrus sinensis*", as expected, as these were the main domain of application for citrus-related papers. The main emerging themes and declining themes were "subtropical region" and "Rutaceae", denoting the importance of modeling and fruit yield prediction in those works. Lastly, the main niche theme was related to "carbon dioxide enrichment", an essential theme for particular applications and domains.

Two important papers in this period that illustrate the basic, motor, and emerging themes identified were [63,64], and [65]. Iglesias et al. [63] performed a risk analysis involving local citrus crops and climate, resulting in good results for public policies. In addition, with a social approach, Miller [64] investigated the reactions and expectations of Florida's citrus growers to freeze events, showing an alignment between extreme events occurrence and citrus management.

Rosenzweig et al. [65] were one of the first to analyze how climate change would impact citrus production, finding negative results in locations where the temperature will rise in winter, such as Florida and Texas. Many studies focused on Florida State in this period due to Florida being the largest citrus-producing state in the USA. This state also faces increasing extreme climate events, such as intense winds and freezing [66,67].

Figure 13 illustrates the second time slice (2011 to 2017). As it contained a considerably larger number of documents, it also presented more themes. The basic themes were "fruit" and "vegetable", as was expected. This reinforces the idea that works focusing on the plants and farm production (instead of, for example, the whole supply chain or other supply chain links) characterize this knowledge domain. Overall, the themes observed in this time slice indicated an increased interest in plant physiology and climate change, with a focus on water management and availability.

The main motor themes identified were: "citrus", "water resources", and "irrigation", denoting the increasing importance of better resource allocation, dealing with water scarcity, and better irrigation techniques. Additionally, some works evaluated the possibility of water scarcity in the future, related mainly to climate change impacts.

The main emerging and declining themes were: "dicotyledon", "human activities", and "agricultural production". These are related to the increase in works that consider the human aspect of farm production and more modern farm management techniques. These are directly connected to the idea of better resource allocation and management. Lastly, the niche themes identified were "agricultural management" and "plantation", encompassing works that focused specifically on the impacts of management on large areas.

One relevant work that represents the basic and motor themes in this time slice is the one from García-Tejero et al. [68]. The authors investigated the effect of limiting evapotranspiration in citrus physiology and production, aiming to propose deficit irrigation as an alternative for management when water scarcity is a problem.

Figure 14 illustrates the thematic map for the time slice from 2018 to 2022. As observed when comparing Figures 12 and 13, there was a considerable increase in the number of themes identified in this period. The main basic themes identified were "climate change" and "ecosystem".

This presents an essential evolution in the research in this area by denoting the increased importance of considering the plants and the whole ecosystem to provide solutions to mitigate the impacts of climate change. This category also encompassed papers on climate change consequences to citrus cultivation, such as abiotic stresses. For example, the effect of climate change on citrus fruits is analyzed in-depth in a literature review by Mitra [69], in which the author also pointed out possible strategies for stress mitigation.

The motor themes identified were: "irrigation" (related to better water management strategies in different regions and climates), "citrus fruits" (related to the increased importance of different types of citrus fruits, such as tangerines, mandarins, and lemons), "population distribution" (related mainly to an increased awareness of the importance of the three pillars of sustainability: economic, social, and environmental), and "carbon sequestration" (related mainly to the importance of designing strategies to reduce the amount of CO_2 in the atmosphere). There are also significant works in land use and land cover change, directly impacting the amount of CO_2 released or captured by a specific area.

The main emerging and declining themes identified were: "hemiptera" (works that explore different diseases caused by pests and their seasonality due to climate variations), "physiology" (composed of physiology studies considering climate variation and different climate scenarios), "chemistry" (composed of studies related to chemical control of pests and pathogens, probably decreasing due to an increase in more sustainable alternatives such as biological control), and "metabolism" (related to the plant's hormone production and associated impacts of climate change).

Lastly, the niche themes identified were: "citrus reticulata" (due to the few papers that are related to this species, even though it has considerable importance in particular parts of the world) and "acari" (mainly related to works exploring how populations of these pests can be affected by climate change). It is important to note that several works in this time slide consider other themes related to climate change besides trying to deal with reducing water availability, such as: CO_2 uptake, sustainability, and pest behavior since pests and their consequent diseases are very important in citrus production [70]. It is also critical to note the importance of more sustainable pest control, as observed by [71,72]. The following section concludes this paper, presenting its final remarks, limitations, and suggestions for future works.

4. Conclusions, Limitations, and Perspectives for the Future

Overall, this bibliometric analysis observed two main gaps in the literature concerning citrus and climate change:

(1) The first gap was the combination of abiotic stresses caused by climate change's increasing impacts on extreme climate events. Most recent studies are related to stresses and their result in plant physiology and, consequently, their production. However, with few exceptions, most studies on abiotic stresses in citrus have focused on the individual effect of these factors, which prevents a prediction of what may occur in the field. Therefore, research that seeks to understand the nature of the various stress responses and create pathways for developing plants and processes that maintain high production levels even under stressful conditions becomes necessary.

(2) The second gap is related to predicting production in different climate change scenarios. Since studies that encompass various stress responses are rare, developing predictive models becomes difficult. The few studies with yield estimation models for citrus are limited to the present scenario or simulations that may not reflect important aspects of real-life scenarios. However, combining stress studies and modeling efforts would lead to better decision-making and management. This would result in more sustainable and profitable crop production.

Our analysis observed that the recent relevance of physiology versus stress studies has increased, as understanding how citrus plants respond to stresses is critical in climate change scenarios. Based on the need to adapt to more frequent and impactful extreme weather conditions, we expect an increase in the number of studies in the future related to the following three aspects: (i) rootstocks and their tolerance to environmental conditions; (ii) management practices such as different types of irrigation methods, use of reflective substances, and fertilizing; and (iii) more ecological and less impacting systems, such as agroforestry.

Finally, some of the main limitations that were observed in this study were: (i) the methodology used, which only considers a quantitative analysis of the selected documents; (ii) not considering languages other than English, as some documents may be developed by Governments and institutions in other languages; and (iii) the lack of research focusing specifically on better understanding the connection between citrus and climate change. However, the methodology adopted in the studies provided relevant results to understand better trends, themes, and the state of the art of research on climate change and citrus.

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