agriculture

Review

Climate Change Impacts on Vegetable Crops: A Systematic Review

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Abstract: Agriculture is a fundamental aspect of our society, providing food and resources for a growing population. However, climate change is putting this sector at risk through rising temperatures, changing rainfall patterns and an increase in the frequency and intensity of extreme weather events. Our study highlights the need to address climate change in a differentiated way, taking into account the specificities of each agricultural sector, and therefore aims not only to organise and summarise current research but also to fill an important gap in the existing literature by focusing on the impact of climate change on vegetable crops. The topic was researched using the Web of Science and Scopus databases, where 219 publications were thoroughly reviewed and only those that fully addressed the impact of climate change on vegetable crops were selected. Of the 219 publications reviewed, only 53 focused exclusively on the effects of climate change on vegetable crops, indicating the need for more specialised research in this area, especially given the complex challenges that climate change poses not only in terms of yield but also non-trivial quality and food safety, and can be considered a future research prospect.

Keywords: literature analysis; environmental factors; climatic disruptions; food security

Citation: Dumitru, E.A.; Berevoianu, R.L.; Tudor, V.C.; Teodorescu, F.-R.; Stoica, D.; Giucă, A.; Ilie, D.; Sterie, C.M. Climate Change Impacts on Vegetable Crops: A Systematic Review. *Agriculture* **2023**, *13*, 1891. https://doi.org/10.3390/agriculture13101891

Academic Editors: Camelia F. Oroian and Horațiu Felix Arion

Received: 21 August 2023
Revised: 25 September 2023
Accepted: 25 September 2023
Published: 27 September 2023

1. Introduction

Climate change is a pressing issue of the 21st century with several implications for both human life and the environment. Agriculture is one of the areas most affected by climate change, and it is a crucial sector for the global economy and food security. Vegetable crops, which play a crucial role in the global food system, can be deeply affected by climate fluctuations [1].

Increasing temperatures are likely to decrease the quantity of desirable crops, whilst fostering the growth of weeds and pests [2]. Alterations in rainfall cycles will increase the probability of short-term crop losses and long-term yield damage [3].

Furthermore, climate change may affect migration patterns, as people may move as a way of adapting to weather-related risks, particularly those affecting agriculture [4]. Subsistence or smallholder farmers in developing countries are among the groups most affected by climate change [5]. The vulnerability of these regions to climate change arises due to their predominantly tropical location, coupled with multiple socio-economic, demographic and political constraints that hinder their capacity to adapt to these changes [6].

Climate change has recently transformed the weed flora of agricultural ecosystems in Europe to a great extent. Thermophilic weeds, late-emerging weeds and certain opportunistic weeds have become more prevalent in certain cropping systems, for example [7]. The composition of weed species is influenced by environmental factors such as temperature and precipitation [8].

Most farmers in Europe are experiencing the impacts of climate change, and these impacts are expected to worsen in the coming decades. The resulting impacts will intensify regional disparities and exacerbate existing climate vulnerabilities. Although limitations on water usage for irrigation and the use of agrochemicals are still in their early stages, they are viewed as more positive from a production standpoint and less positive from an environmental standpoint [9].

Furthermore, climate change is expected to result in physical and economic repercussions in Europe. Specifically, these will fall into four categories of market impacts, namely agriculture, river flooding, coastal areas and tourism, as well as one non-market impact, human health. It appears that climate change will affect the southern regions of Europe, the British Isles and North Central Europe the most [10]. In contrast, Northern Europe is the only region that has net economic benefits, mainly due to the positive effects on agriculture [11].

Vegetable crops are crucial for human nutrition as they provide essential nutrients and are a fundamental constituent of the daily diet [12,13]. Nonetheless, these crops are exceedingly sensitive to climate change, particularly to increasing temperatures, which can directly impact their yield [14]. To address the challenges of climate change, it is crucial to develop vegetable varieties that are heat-resistant [12,15].

Climate change is significantly impacting the global vegetable sector, and Europe is not an exception. A study by Reidsma et al. (2015) [16] emphasized the need for integrated assessments and analysis of farming systems, considering adaptation at different levels, as a basis for assessing the impacts of climate change on agriculture. Despite crop modelling indicating positive impacts of climate change on major crop yields in 2050 [17], a semi-quantitative and participatory approach evaluating the effects of extreme events demonstrates the presence of several climate risks [6]. Several adaptation measures are available to mitigate potential negative impacts on crops. Moreover, farmers at the farm level can modify their cropping patterns and adjust their inputs and outputs [18].

In their 2016 study, Harrison et al. [19] pointed out that climate change impact assessments that focus only on isolated sectors such as agriculture, forestry and water management, without considering how they interact, tend to give a distorted picture of the real effects. This is especially significant for the vegetable sector as it is closely connected to other sectors through changes in demand, land matching and the competition for resources.

As climate change continues to evolve, it is of utmost importance to understand how it could affect various types of vegetable crops. For instance, some vegetables may exhibit higher resilience to specific climatic conditions than others. Differences of this nature could have considerable implications for climate change adaptation strategies [20]. Furthermore, alterations in precipitation and temperature can impact the lifecycle of pests and illnesses, which may have an additional impact on the yield and the quality of vegetable crops [21].

Moreover, certain studies imply that implementing heat-resistant strains of Trichoderma could serve as a sustainable solution to tackle climate change in vegetable farming [22]. This emphasises the significance of investigating climate change adaptation in agriculture and the urge to create new strategies to safeguard vegetable crops (Figure 1).

Figure 1. Effects of climate change. Source: Own processing after: [23–26].

Vegetable crops such as tomatoes, potatoes, onions and cabbage play a vital role in providing food and supporting local economies. Thus, understanding their sensitivity to climatic variations is crucial in devising strategies to safeguard and adapt them against future environmental challenges [27]. High temperatures and drought can cause heat stress in plants, which has a direct impact on their health and growth [28].

The aim of this study is not only to organise and summarise current research but also to fill an important gap in the existing literature by focusing on the impact of climate change on vegetable crops. It places particular emphasis on identifying effective methods of disease and pest control, strategies for soil conservation and water management and discovering technologies and innovations for sustainable horticulture. Our study highlights the need to address climate change in a differentiated way, taking into account the specificities of each agricultural sector. This is crucial because climate change affects agricultural sectors differently, whether cereals, vegetables or fruit, and each requires specific adaptation and mitigation strategies, thus contributing to a more nuanced understanding of how the vegetable sector will be affected.

2. Materials and Methods

To conduct the study, we carried out a systematic review of papers exploring the impact of climate change on vegetable crops. This review aimed to identify how researchers have approached this topic. The review was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses reporting checklist [29,30].

To achieve the study's aim, a comprehensive search was conducted on 219 scientific articles in the Web of Science and Scopus databases, out of a total of 107,799 scientific publications on the general topic of "climate change impacts" from 1990 to 2023. The search focused on the effects of climate change on vegetable crops and imposed no restrictions on date or language. Despite a large body of research examining the impacts of climate change on agriculture as a whole, there is a notable gap in the scientific literature when it comes to the impacts on vegetable crops. Many of the existing studies tend to generalise the effects of climate change on the agricultural sector, without looking at the specifics of particular crop types. This generalisation can be problematic because vegetable crops may be more sensitive to changes in temperature, precipitation and other climatic factors than other crops [31]. This increased sensitivity not only raises questions about the long-term viability of these crops but also has serious implications for food security and public health. It is therefore imperative to have a more detailed and focused understanding of how climate change specifically affects vegetable crops in order to formulate effective adaptation and mitigation strategies. Consequently, the title, abstract, keywords, journal name, and year of publication were exported in a spreadsheet [30].

The subsequent action was to assign the spreadsheet to two assessors, whose task was to analyse the downloaded titles and abstracts independently, check their eligibility concerning the subject under review and reject those that did not meet the criteria [29]. A total of 89 records not specifically related to the impact of climate change on vegetable crops have been removed and we only retained articles that exclusively deal with vegetable-related issues for the literature review (Figure 2).

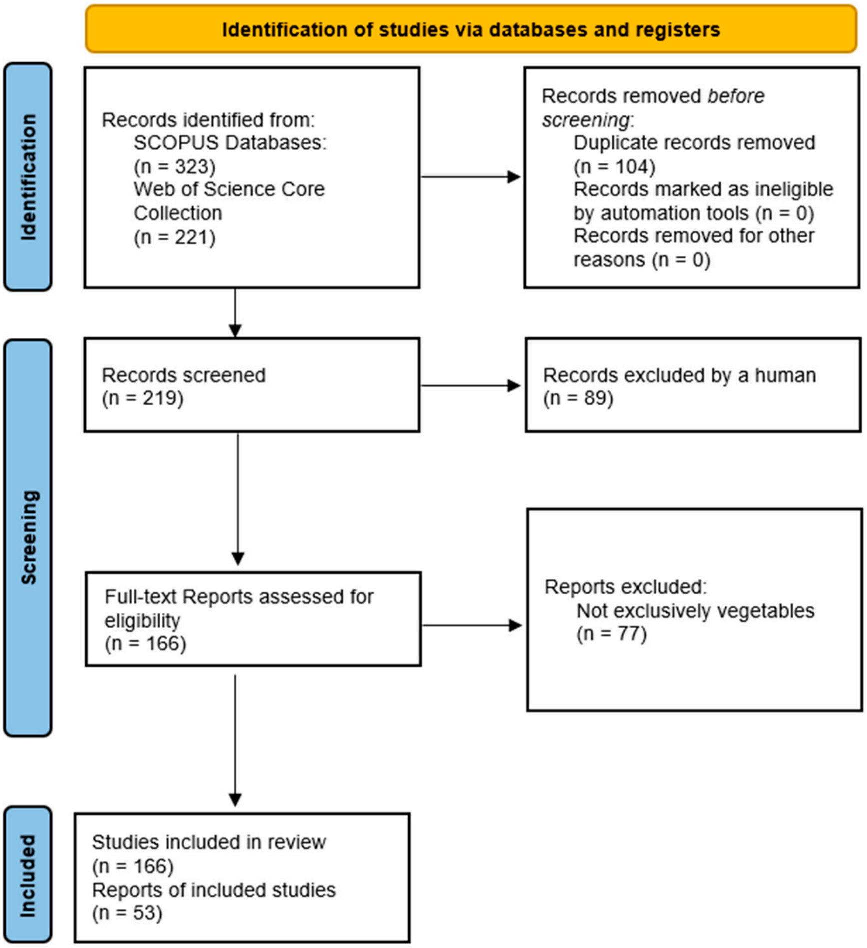

Figure 2. PRISMA 2020 flow diagram for the current study [29].

The papers were reviewed completely and independently in the same manner. Note that any disagreements between the reviewers were resolved through discussion and consensus. If the reviewers could not reach a consensus, a third independent reviewer would have been consulted to review the articles in question.

3. Results

Analysing the number of empirical research publications on the impact of climate change on vegetable crops, a substantial increase can be observed since 2015 (Figure 2). This upward trend likely reflects a growing awareness of the effects of climate change on agriculture, as well as the recognition of the importance of this topic in policies at European and global levels. The increase in the number of publications in this field indicates an increased focus of research efforts on the impacts of climate change on vegetable crops, peaking in 2022 (Figure 3).

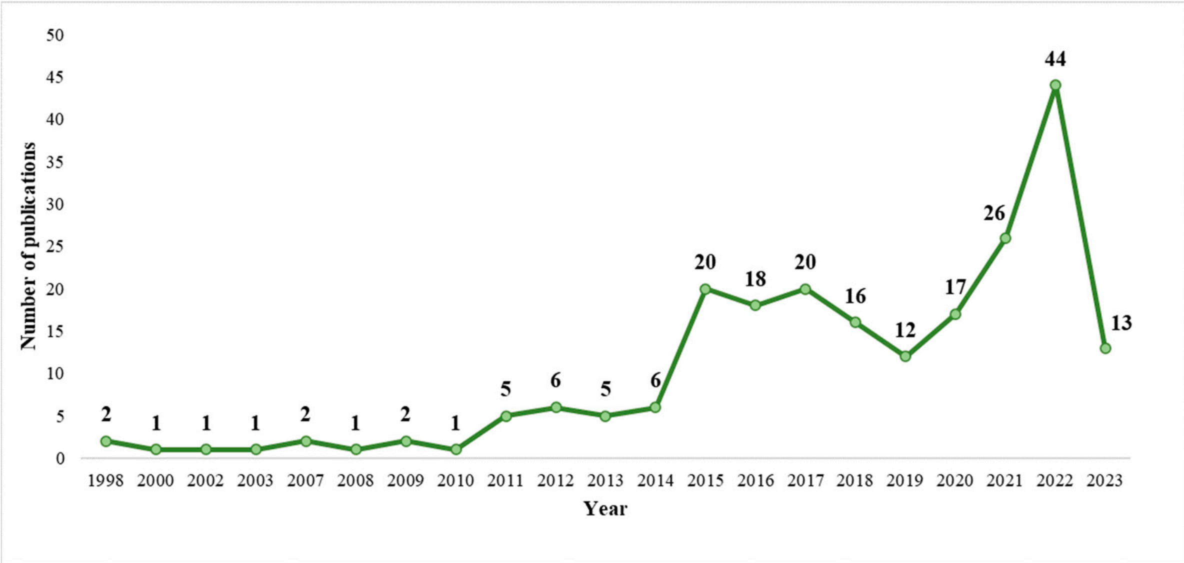

Figure 3. Number of empirical research publications on the impact of climate change on vegetable crops by year.

In terms of the geographical context of empirical research on the impact of climate change on vegetable crops, it can be seen that most of the research comes from highly industrialised countries with rapidly growing populations, such as the USA, India, China, England and Germany. This suggests that climate change and food security are major issues in these countries, likely due to the combined pressures of industrialisation, population growth and the need to ensure food security. In addition, these countries have the resources and capacity to conduct extensive research on this topic (Figure 4).

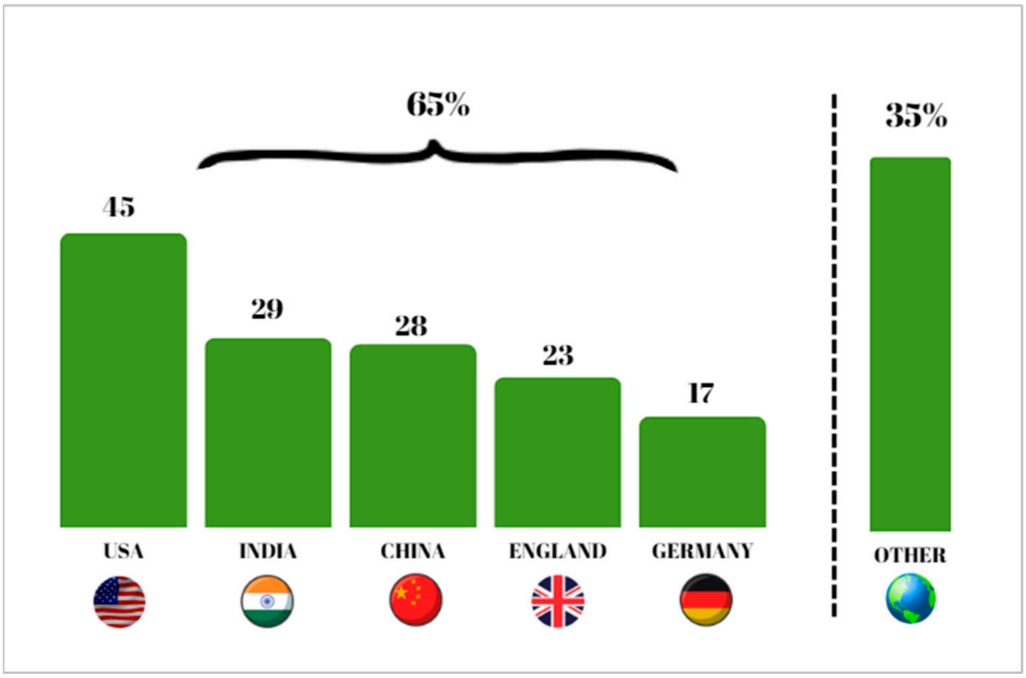

Figure 4. Geographical context of empirical research on the impact of climate change on vegetable crops.

The distribution of empirical research publications in the field of climate change on vegetable crops shows that this field is interdisciplinary, involving several scientific disciplines. The majority of studies (31.1%) are in the field of environmental sciences, which underlines the importance of understanding the ecological context in which climate change takes place. At the same time, a significant proportion of the studies (15.1%) are in the field of agronomy, indicating a focus on the impact of climate change on agricultural practices and technologies. In addition, 11.9% of the studies are in plant sciences, suggesting a focus on the effects of climate change on plant physiology and biology (Figure 5).

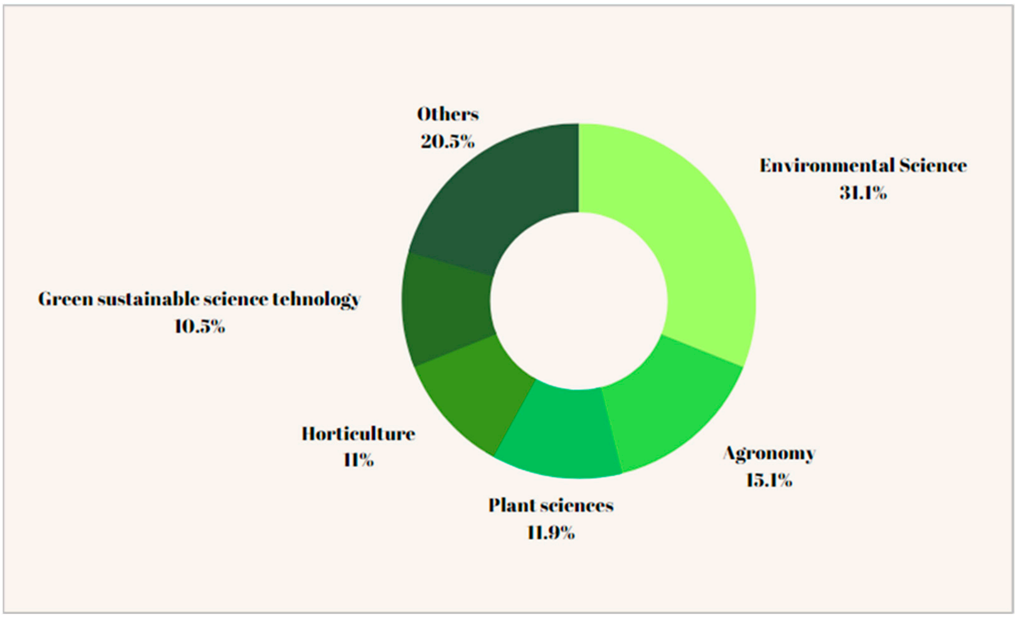

Figure 5. Share of empirical research publications on climate change on vegetable crops.

Using VosViewer version 1.6.19 software, maps were generated with the keywords used in the research, mentioned at least 5 times, and grouped into clusters. It shows the words related to our topic, grouped into clusters based on semantic similarities between words, the size of the nodes representing the frequency of keywords and the length and thickness of the lines between words showing the degree of association between them [32].

The first cluster (red) named, "yield", includes tomato, nitrogen, vegetable, carbon dioxide, growth, drought, maize, plants, quality, heat stress, salinity, high-temperature, drought stress, elevated co2 and air co2 enrichment. The keywords contained in this cluster present two research directions, namely, the increased interest in plants and vegetables and the effects of climate and stress on them.

Cluster two (green), called "agriculture", includes consumption, productivity, management, use efficiency, diversity, farmers, impact, land use, climate, stress and food security. These words indicate researchers' concerns about the effects of climate change on agriculture in general, consumption and food security.

Cluster three (blue), called "irrigation", includes food, wheat, greenhouse gas emission, model, system, performance, sustainability, environmental impact and life cycle assessment. Thus, it can be said that irrigation is a complex topic covering efficiency, environmental and life cycle issues.

Cluster four (yellow), called "climate change", includes temperature, adaptation, variability, rice, trends, precipitation, soil and responses, and cluster five, (purple) called "impacts", includes crops, global warming, systems, water and vulnerability (Figure 6). It should be noted that the keywords appearing in Figure 6 that are not related to vegetable production are determined by the studies analysed that take a broader approach to the agricultural sector as a whole, which were subsequently eliminated in the aggregation process.

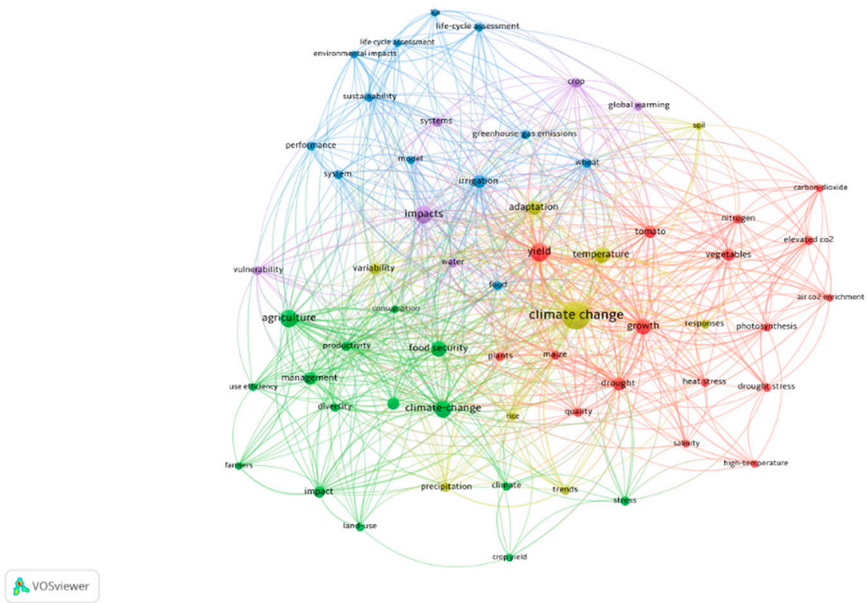

Figure 6. Link between "Climate change impact on vegetable crops" and other related terms. Source: Own processing based on WoS results using VOSviewer.

The following are the keywords that researchers used in 2016–2020: Wheat, soil, nitrogen, carbon dioxide, elevated co2, responses and photosynthesis. In 2018 and 2019, researchers focused on adaptation, climate change, yield, temperature, food security, plants, productivity, agriculture, management, use efficiency, vulnerability, impact, irrigation, performance, sustainability, life cycle assessment, crop, vegetable and salinity. Later, in 2020, researchers were concerned about topics such as stress, climate change, crop yield, precipitation, land use, farmers, heat stress, tomato, food, model and system (Figure 6). It is worth noting that since 2020, keywords such as 'stress', 'farmers', 'heat stress' and 'food' have become more prevalent, which may be due to the COVID-19 pandemic putting additional stress on agricultural systems, farmers and food security (food), which has increased researchers' attention on these issues (Figure 7).

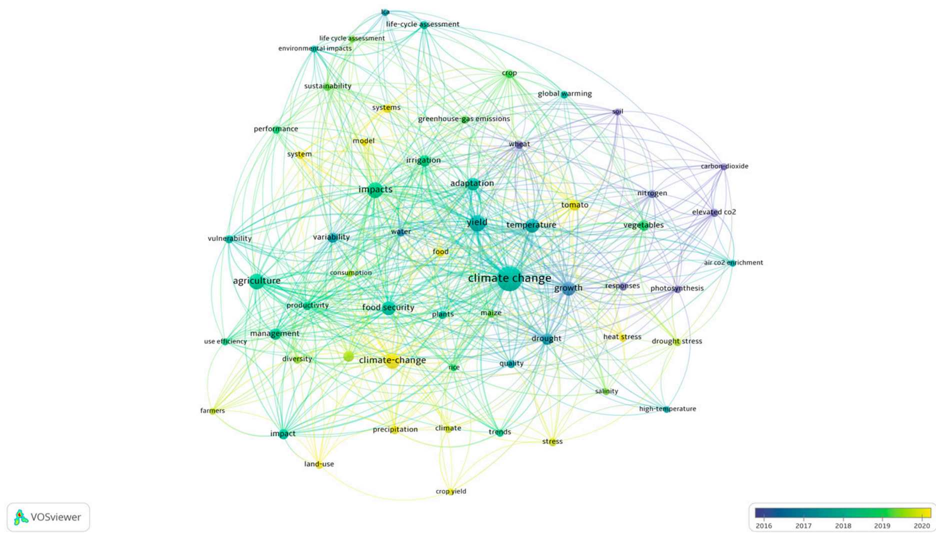

Figure 7. Relationship between "Climate change impact on vegetable crops" and other related terms by year. Source: Own processing based on WoS results using VOSviewer.

Out of a total of 219 publications analysed, 89 were excluded because, although they dealt with the effects of climate change, they did not focus specifically on the topic of "vegetables". This resulted in 130 articles meeting the established criteria. Of these 130 articles, 77 included vegetables in their discussion of climate change but did not focus exclusively on this topic. In this category, the majority of articles (53) were of the "Article" type, followed by "Review" (11), "Proceedings Paper" (8), "Article; Book Chapter" (4) and "Article; Data Paper" (1) (Table 1).

Table 1. Distribution of types of research papers on the impact of climate change on vegetable crops.

Approach	Document Type	1998–2002	2003–2007	2008–2012	2013–2017	2018–2023	Total
Including vegetables	Article	1	-	5	10	37	53
	Article; Book Chapter	-	-	1	3	-	4
	Article; Data Paper	-	-	-	-	1	1
	Proceedings Paper	1	-	-	4	3	8
	Review	1	-	1	3	6	11
Total		3	0	7	20	47	77
Exclusive vegetables	Article	-	-	-	9	18	27
	Article; Book Chapter	-	-	-	1	1	2
	Article; Proceedings Paper	-	1	-	-	-	1
	Proceedings Paper	-	-	2	5	2	9
	Review	-	-	-	2	12	14
Total		0	1	2	17	33	53
Excluse	Article	-	1	1	20	29	51
	Article; Book Chapter	-	-	-	1	2	3
	Article; Proceedings Paper	-	-	-	1	-	1
	Editorial Material; Book Chapter	1	-	-	-	-	1
	Proceedings Paper	-	1	2	7	1	11
	Review	-	-	3	2	16	21
	Review; Book Chapter	-	-	-	1	-	1
Total		1	2	6	32	48	89
Total general		4	3	15	69	128	219

In contrast, 53 articles dealt exclusively with the effects of climate change on vegetable crops. In this category, the majority of articles were of the "Article" type (27), followed by "Review" (14), "Proceedings Paper" (9), "Article; Book Chapter" (2) and "Article; Proceedings Paper" (1). In terms of the distribution over time, a significant increase in the number of publications can be observed over the period of 2018–2023, both for articles that include vegetables in their discussion of climate change and those that focus exclusively on this topic (Table 1).

The next step was to collect and analyse publications that exclusively address the effects of climate change on vegetable crops (n = 53) and to rank them in descending order of citations, being ranked in descending order of citations, while also being considered a ranking criterion according to their importance, highlighting objectives, methods and results in the simplest possible way (Table 2).

Table 2. Summary of evidence and findings ranked in descending order of citations.

Authors	Year of Publication	Citations	Objectives	Methods	Results
Jung, Y.J.; et al. [33]	2014	114	Microbiological risk assessment of vegetables	Analysis of disease outbreaks and laboratory studies	Potential increase in risks due to climate change
Tasca, A.L.; et al. [34]	2017	83	Comparing the environmental impact of two supply chains	Comparing organic and integrated production	The need to improve organic farming techniques
Alliaume, F.; et al. [35]	2014	71	Impact of different soil management practices	Field study with four soil management practices	Significant reduction of run-off and soil erosion
Liu, Y.W.; et al. [36]	2022	62	Climate prediction in greenhouses	Model LSTM	Robust, more efficient model
Neira, D.P.; et al. [37]	2018	38	Energy use and carbon footprint analysis	Life cycle analysis	Increasing productivity but also energy demand and carbon footprint
Malhotra, S.K. [17]	2017	33	Climate change impact assessment	Analysis of physiological responses	The need to adapt horticulture
Malhi, G.S.; et al. [38]	2021	33	Climate change impact investigation	Arbuscular mycorrhizal association examination	Mycorrhiza improves plant stress tolerance
Azam, A.; et al. [39]	2013	32	Impact of atmospheric CO2 on yield and nutritional quality	Yield assessment under increased CO2 conditions	Evaluation of yield and chemical characteristics under increased CO2
Shrestha, R.P. and Nepal, N. [40]	2016	25	Impact of climate change on food security	Climate data analysis, interviews, group discussions	Climate change affects food security
Cammarano, D.; et al. [41]	2020	24	Agricultural crop simulation model evaluation	Use of field data, selection of climate projections, use of DSSAT model	Model successfully simulated tomato response to nitrogen fertilization
Silva, R.S.; et al. [42]	2017	23	Assessing the impact of climate change on tomato cultivation	Use CLIMatic indEX climate model, A2 emissions scenario, CSIRO-Mk30 climate model	Current favourable areas will become unsuitable for tomato growing
Min, J.; et al. [43]	2016	17	Estimation of global warming potential in vegetable growing system	Comparative field experiment	Changing crop rotation reduced N2O emissions and increased economic benefit
Tarek, H.; et al. [44]	2022	16	Identification of tomato diseases	Evaluation of pre-trained models	98.99–99.81% accuracy
Potopova, V.; et al. [45]	2017	16	Temperature and precipitation response estimation	Statistical analysis of historical data	Positive effects of warming
Ahmad, W.; et al. [46]	2019	13	Understanding stress tolerance in cabbage	NaCl stress testing	Growth and regulation of mechanisms under saline conditions
Jasper, J.; et al. [2]	2020	13	Impact of temperatures on arugula	Growing at different temperatures	Arugula survival decreases at 40 °C
Bisbis, M.B.; et al. [47]	2019	12	Climate impact assessment on crops	Literature review	Negative impact of climate change
Litskas, V.D.; et al. [48]	2019	10	Climate impact on tomatoes	Modelling irrigation conditions	Potential for red spider mite outbreaks increases
Schmidt, N. and Zinkernagel, J. [49]	2017	9	Impact of climate on onion irrigation	Simulation of various scenarios	Increasing water demand
Perez-Alfocea, F. [50]	2015	9	Increasing agricultural productivity	Study of plant interactions	Contributing to sustainable agriculture
Saeed, F.; et al. [12]	2023	8	Heat-resistant vegetables	Omics technologies and genomic editing	Vegetables more resistant to high temperatures

Table 2. *Cont.*

Authors	Year of Publication	Citations	Objectives	Methods	Results
Hoshikawa, K.; et al. [51]	2021	7	Climate impact on food security	Literary review	Reducing production and genetic diversity
Stoilova, T.; et al. [52]	2019	7	The role of seed kits in supporting agriculture	Distribution and monitoring of seed kits	Increasing vegetable diversity
Koundinya, A.V.V.; et al. [53]	2018	6	Climate change adaptation strategies	Analysis of genomics and phenomics	Multiple adaptation strategies identified
Cecilio, A.B.; et al. [54]	2022	6	Effect of nitrogen on growth and greenhouse gas emissions	Evaluation of nitrogen efficiency	Higher winter beet productivity
Kim, S.; et al. [55]	2021	5	Impact of climate on broccoli production	Plant-oriented cropping pattern	Close yield linked to nitrogen application
Abdelkader, M.; et al. [56]	2022	4	Energy footprint and greenhouse gas emissions in vegetable production	Analysis of energy consumption and GHG emissions	Potato production has the lowest environmental impact
Kazandjiev, V. [57]	2017	3	Maximising yield by controlling the plant growth environment	Protected cultivation techniques	Successful growing of fruit and vegetables under controlled conditions
Lohr, V.I. [58]	2014	3	Assessing awareness of climate change in horticulture	Survey on the inclusion of climate change in courses	Most programmes do not offer specific courses on climate change
Singh, D.P.; et al. [59]	2022	3	Exploring metabilome to improve vegetable crop performance	Metabilomic analysis technologies	Identification of metabolic biomarkers for improved molecular crop improvement
Ma, M.X.; et al. [60]	2023	2	Examining the impact of soilborne pathogens on the processing tomato crop	Literature review	Identification of various management methods for disease control
Yonekura, T.; et al. [61]	2005	2	Investigating the effects of O3 and CO2 on the growth of komatsuna and radish crop plants	Exposure of plants to different levels of O3 and CO2	O3 reduced leaf area and biomass, while CO2 significantly increased biomass
Singh, A.K.; et al. [22]	2022	2	Understanding the molecular mechanisms of heat resistance in tomatoes	Scientific literature review	Identifying the importance of generative tissue research and genetic and epigenetic mechanisms in heat resistance
Hansen, L.S.; et al. [62]	2022	2	Analysis of gardening in sub-Saharan Africa	Literature review	Variation in home gardens
Jaenicke, H. and Virchow, D. [63]	2018	2	Analysis of the role of horticulture in sustainable development	Evaluation of the SDGs	Horticulture contributes to several SDGs
Le Quillec, S.; et al. [64]	2011	2	Evaluating the effectiveness of a temperature strategy	Studies from 2006–2008	Energy consumption reduced by 5–15%
Lee, K.; et al. [65]	2022	2	Impact of heat stress on tomatoes	Review of studies	Negative impact on yield
Temmen, J.; et al. [66]	2022	1	Evaluation of ocean drift of sweet potato	Laboratory and numerical experiments	Feasible, but seed viability decreases
Saqib, M. and Anjum, M.A. [67]	2021	1	Impact of planting date on sweet pepper	Evaluation of transplants	Better performance in early plantings
Lounsbury, N.P.; et al. [68]	2022	1	The efficiency of prelayers in cabbage production	Cover crop + use of tarpaulins	Heavier cousin in no-till system
Perez-Alfocea, F. [69]	2021	1	The potential of grafting in vegetable production	Identification of problems that can be solved by grafting	Propose tolerable root to parasitic broomrapes

Table 2. *Cont.*

Authors	Year of Publication	Citations	Objectives	Methods	Results
Bhusal, K.; et al. [70]	2022	1	Adapting to climate change in Nepal	Participatory field assessment	30.5% and 31.1% increase in bitter harvest
Kumar, P.; et al. [71]	2021	1	Economic analysis of protected cultivation in Uttarakhand	Survey and focus group discussions with 96 farmers	Protected cultivation is a highly profitable activity
Joshua, M.D.K.; et al. [72]	2020	0	Sustainable technologies to improve vegetable production in peri-urban context	Participatory Action Research (PAR) approach	Significant improvements in vegetable production
Van Loon, J.; et al. [73]	2012	0	Influence of daily weather variations on the use of decision support systems	Development of a cauliflower growth model	Proposed framework for using a cauliflower growth model with minimum data
Choudhary et al. [74]	2015	0	Climate stress resistance of vegetables	Identification of resistant germplasm	Holistic approach needed
Klostermann, H.R.; et al. [75]	2015	0	CO2 impact on vegetable productivity	Experiments in the FACE facility	Results not yet available
Yang, Q.H.; et al. [76]	2016	0	Assessment of heavy metal pollution	Plasma mass spectrometry	Heavy metal content determined
Tang, R.L.; et al. [77]	2023	0	Adaptation of the WOFOST model for chilli peppers	Use of field data from 2021	Good growth simulation
Flores-Saavedra, M.; et al. [78]	2023	0	Review of water stress induction methods	Analysis of stress induction techniques	Water stress affects crop performance
Carrasquilla-Batista, A.; et al. [79]	2016	0	Introducing IoT in greenhouses	Integration of an IoT platform	Improved drainage measurements
Siomos, A.S.; et al. [80]	2022	0	Highlighting climate impacts on broccoli	Analysis of temperature requirements	The significant impact of climate change
Manea, V.; et al. [81]	2022	0	Identification of organic fertiliser alternatives	Chemical analysis of onion bulbs	Effectiveness of organic diatomite and Trichoderma

Based on the synthesis shown in Table 1, taking into account the results identified, four topics were determined according to how the effects of climate change on productivity are addressed (Figure 8).

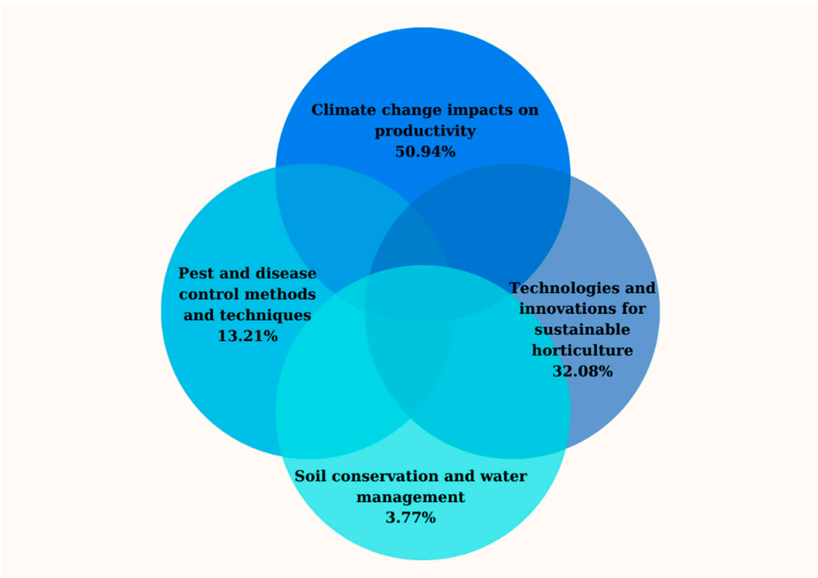

Figure 8. Topics covered in the synthesis of articles based exclusively on the impact of climate change on crop production.

3.1. Impact of Climate Change on Productivity

Recent studies indicate that climate change is significantly impacting vegetable productivity. The effect of climate change on vegetable microbiological safety was highlighted by Jung, Jang and Matthews (2014) [33], who reported that it increases the ability of pathogens to persist in soil, water and crops, thus posing risks to human health. Meanwhile, Shrestha and Nepal (2016) [40] found evidence of climate change negatively impacting farming communities in Makwanpur district, Nepal, putting their food security at risk. Heat stress and droughts are expected to render many areas that currently have optimal climates unsuitable for open-field tomato cultivation in the future [42]. Based on historical climate data, they estimated the temperature and precipitation response of vegetables, with positive results for fruiting vegetables but decreased yield stability of vegetables (root vegetables) [45].

Jasper, Wagstaff and Bell (2020) [2] reported that glucosinolate biosynthesis and the formation of hydrolysis products after harvest are significantly affected by growth temperatures. Specifically, a high growth temperature (40 °C) was found to significantly reduce the germination, growth, regeneration and survival of arugula plants. Bisbis, Gruda and Blanke (2019) [47] determined that global warming will have consequences for physiological processes, such as vernalization and winter chilling, of vegetables, which are highly temperature-dependent, indicating the impact of climate change on horticultural crops.

3.2. Pest and Disease Control Methods and Techniques

Various methods and techniques can be used to control diseases and pests in vegetable production, particularly given the challenges posed by climate change. In a study by Tasca, Nessi and Rigamonti (2017) [34], the environmental impacts of two endive supply chains, one organic and the other integrated, were compared. The results showed that neither cultivation technique displayed a clearly superior environmental profile. This emphasises the necessity of enhancing organic farming techniques, particularly with respect to fertilisation practices.

Arbuscular mycorrhizae can be used as a method of disease and pest control by improving plant tolerance to abiotic stresses, as proposed by Malhi and colleagues in 2021 [38]. Litskas and colleagues (2019) [36] simulated the impact of climate change on tomato production and related pests, indicating that in several parts of the world, future environmental conditions might become unsuitable for tomato cultivation.

The effectiveness, specificity, longevity and public acceptance of biological control against soil-borne pathogens like Fusarium oxysporum and Pythium species, which have significant negative impacts on tomato yield and growth, have caused an increase in attention to this method. Additionally, Temmen et al.'s (2022) [66] study evaluated the feasibility of ocean drift as a means of introducing South American sweet potato seed pods to the Pacific Islands, revealing the potential of this method for colonizing new regions.

Grafting, a technique discovered and implemented in the early 20th century, has been mainly used in high-value crops such as solanaceous and cucurbitaceous to mitigate soil diseases and extend early or late yields through rootstock-mediated vigour. According to Perez-Alfocea (2021) [48], the potential for the use of grafting in vegetables worldwide is still vast. However, further development will depend on its ability to address major societal challenges, including ensuring food production for the growing population, combatting malnutrition, conserving natural resources and mitigating and adapting to climate change.

3.3. Soil Conservation and Water Resource Management

Effective soil conservation and water resource management play a crucial role in sustaining agricultural productivity, particularly in the face of climate change. Al-liaume et al. (2014) [35] analysed the impact of varied soil, crop residue and organic matter management techniques on runoff, soil erosion, water dynamics and productivity in a system of tomato–oat rotation on raised beds. Their findings showed that practices like reduced tillage, the use of mulched cover crops and chicken manure incorporation significantly lowered soil erosion and runoff by over 50% compared to the three traditional tillage systems. Nevertheless, conventional tillage with chicken manure integration produced the highest yield, exceeding the reduced tillage by over 50%.

Furthermore, the implementation of contemporary technologies like the Internet of Things (IoT) can enhance the management of water resources in greenhouse horticulture. According to Carrasquilla-Batista et al. (2016) [78], IoT resources were investigated to enhance the precision of drainage measurements in greenhouse horticulture. The researchers integrated IoT capabilities into a greenhouse, thereby providing a platform for timely decision-making by researchers concerning irrigation, moisture and nutrient requirements.

3.4. Technologies and Innovations for Sustainable Horticulture

The role of technologies and innovations is paramount in promoting sustainable horticulture amidst climate change. Malhotra (2017) [17] highlights the necessity of a climate-adapted intervention in horticulture, which incorporates location-specific and intensive knowledge to enhance production under challenging conditions.

Using a crop simulation model, Cammarano et al. (2020) [41] evaluated the effect of climate change on water and nitrogen use efficiency in processing tomato crops cultivated in Italy. Their findings suggest that as a result of projected increases in air temperature and precipitation fluctuations, the phenology of tomatoes was reduced by 1.5 to 3 days, ultimately causing an overall 15% decline in tomato yield. In a related study, Min et al. (2016) [43] estimated the global warming potential in an intensive vegetable cropping system that was influenced by crop rotation and the nitrogen rate. Their research indicated that global warming potential can be reduced while maintaining agricultural economic benefits by optimising vegetable crop rotation through the inclusion of legumes and adjusting nitrogen application rates.

Nevertheless, contemporary technologies such as deep learning and the Internet of Things (IoT) can be employed to enhance sustainable horticulture. Tarek et al. (2022) [44] assessed several pre-trained deep learning models to detect tomato diseases and noted that both MobileNetV3 Small and Large models achieved over 98% accuracy. Furthermore, Ahmad et al. (2019) [46] investigated the impact of supplementary potassium on the antioxidant defence system and physiological processes that could affect cabbage cultivation in saline conditions.

Perez-Alfocea (2015) [50] concludes that agrarian productivity should increase by 60% to sustain the estimated 9.6 billion population in 2050. This target can only be accomplished via socio-environmental sustainability of natural resources. The text suggests that the primary objective of vegetable grafting investigation should be to ascertain a firm comprehension of the physiological and genetic foundation of rootstock–graft interactions and the agronomic performance of the rootstock-mediated traits.

Regarding the geographical context of the research, most studies originate from highly industrialised countries with rapidly growing populations, comprising the USA, India, China, England and Germany. This indicates that climate change and food security are major concerns in these nations, likely due to the combined pressures of industrialisation, population growth and the imperative for ensuring food security.

In a changing world, where climate change is having a significant impact on vegetable productivity, there are complex challenges. These challenges not only affect yield but also have significant impacts on nutritional quality and food safety. The degree of impact varies depending on the geographical context, type of vegetable and growing conditions.

Disease and pest control become essential in this landscape to maintain productivity in the face of climate change. Organic farming, biological control, grafting and the use of arbuscular mycorrhizae are emerging as promising techniques that can improve the resilience of vegetable crops to climate change.

Simultaneously, soil conservation and efficient water resource management are proving to be crucial components of climate change adaptation. Through low-tillage techniques, the use of mulch and the incorporation of organic matter, farmers can help reduce soil erosion and improve water retention.

The Internet of Things (IoT) and other emerging technologies have the potential to play a crucial role in managing resources efficiently and increasing productivity. Integrating these technologies into vegetable production systems could enable researchers and farmers to make faster and better-informed decisions about irrigation, moisture and nutrient requirements.

4. Conclusions

The geographical distribution of these studies shows a significant bias towards highly industrialised countries such as the US, India, China, the UK and Germany. While this could be attributed to higher levels of scientific activity and funding in these countries, it also highlights a critical research gap in less industrialised or developing countries, where the impacts of climate change could be even more severe due to fewer resources for adaptation.

The interdisciplinary nature of the existing literature, ranging from environmental sciences to agronomy, suggests a comprehensive approach to understanding the ecological and practical aspects of climate change impacts. However, the focus remains largely on crop yield, with less attention paid to other critical factors such as nutritional quality, food safety and pest and disease control.

Of the 219 publications reviewed, only 53 focused exclusively on the effects of climate change on vegetable crops. Furthermore, despite the low number of related studies (53), many of these have not received adequate attention in terms of citations (see Table 2). This points to the need for more specialised research in this area, especially given the complex challenges that climate change poses not only to yield but also to nutritional quality and food safety.

Future Research Perspectives

- Geographical bias: Most studies are from developed countries, which limits the applicability and global relevance of the results. It is essential to extend research to developing countries and regions with different climates. This would provide a more nuanced understanding of how climate change affects vegetable crops in different geographical and socio-economic contexts.
- Crop diversity: Focusing on a limited number of crops, such as tomatoes, limits the general applicability of the results. Future research should include a wider variety of vegetables to better understand species-specific adaptations and develop more comprehensive adaptation strategies.
- Nutritional quality: Few studies address the impact of climate change on the nutritional quality of vegetables. A detailed investigation of how climate change may affect the nutritional composition of vegetables, including vitamins, minerals and antioxidants, is needed.
- Technological integration: While emerging technologies such as the Internet of Things are promising, their practical applicability remains underexplored. Further studies are needed to assess the effectiveness and feasibility of integrating emerging technologies into vegetable production systems, particularly in resource-constrained contexts.
- Funding and scientific activity: The large volume of research in developed countries may lead to bias in the perception of where climate change impacts are most severe or most studied. Future research should take account of this bias and seek to provide a more balanced global perspective, including exploring alternative sources of funding and international collaborations.

Author Contributions: Conceptualization, E.A.D., R.L.B. and V.C.T.; methodology, E.A.D. and C.M.S.; software, D.S. and D.I.; validation, A.G. and C.M.S.; formal analysis, R.L.B. and E.A.D.; writing—original draft preparation, E.A.D. and F.-R.T.; writing—review and editing, D.S. and A.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Agriculture and Rural Development (Romania), under contract ADER 22.1.3/21.07.2023—"The economic efficiency in small and medium-sized farms of production technologies in an ecological system for the main horticultural and vegetable crops in Romania in order to reduce the effects of climate change".

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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