



Computable general equilibrium implementation in agriculture under the prism of sustainability and climate change: a systematic literature review

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Abstract

Given the challenges posed by climate change and resource overexploitation, sustainable solutions in agriculture requires integrated tools that harmonize economic viability with ecological stewardship. Previously, policies prioritized maximization of short-term productivity, leading to significant resource depletion and soil degradation. In this context, bioeconomic models, particularly Computable General Equilibrium (CGE) models, have emerged as essential tools for assessing the interconnection among the tripartite pillars of sustainability. This study aims to evaluate CGE implementation in agriculture by defining comprehensive criteria, analyzing the Water-Energy-Food-Ecosystem (WEFE) Nexus integration across the pillars of sustainability, and providing a roadmap for future research. Therefore, this study employs a Systematic Literature Review (SLR), assessing 131 full-text studies for eligibility from an initial pool of 9,673 documents. Of these full-text studies, 115 papers were selected for inclusion and classified into 8 thematic categories and 30 defined criteria, which enhance the accuracy of CGE implementation outcomes. Results indicate that while CGE implementation predominantly evaluates economic impacts (97%), it increasingly internalizes environmental (54%) and social (43%) pillars. A critical insight rooted in this study is the transformative role of the WEFE Nexus, and particularly, food security acts as a multidimensional bridge linking environmental ($p=0.013$) and social impacts ($p=0.037$), while water management serves as a foundational cross-cutting driver across all sectors. Integrating the WEFE Nexus into CGE models enhances climate mitigation efficacy by quantifying critical trade-offs between economic growth and resource preservation, as well as capturing the concurrent interdependencies between Nexus pillars. Finally, this SLR identifies existing research gaps, including the ineffectiveness of capturing granular, real-time farmer behavioral responses and localized technological adoption rates, and recommends further scientific pathways for CGE modeling with a view to agricultural sustainability. Further research should focus on the concurrent implementation of CGE modeling approaches with, for instance Agent-Based Modeling (ABM), Machine Learning, and Artificial Intelligence (AI) techniques to improve the spatial resolution of climate-impact simulations.

Keywords Computable General Equilibrium (CGE) models · Sustainability · Water-Energy-Food-Ecosystem (WEFE) Nexus · Climate change · Optimization · Resource management

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1 Introduction

Globally, agricultural systems are facing unprecedented challenges, including water scarcity, energy crisis, food insecurity, and environmental degradation, exacerbated by a steady increase in average global temperatures (Singh 2021). While these impacts are detrimental in a global scale, regions with fragile environmental balances, such as the Mediterranean, are experiencing particularly acute manifestations of these shifts (Pathak 2023). The agricultural sector remains highly susceptible to climate change, resource depletion, and reliance on non-renewable energy. Addressing these challenges requires urgent adaptation measures to mitigate their negative impacts (Malhi et al. 2021; Raviv et al. 2024). Apart from the agricultural sector, the implications of climate change affect a multitude of sectors worldwide; thus, effective cooperation and coordination of the European countries is required (United Nations. Climate Action, 2021). Furthermore, there is an urgent need to efficiently use and preserve water, energy, food, and ecosystem resources, promote sustainable development, and integrate climate change measures into national policies, strategies, and planning, all in complete accordance with the Sustainable Development Goals (SDGs) and the Common Agricultural Policy (CAP) 2023-27 context (European Commission, 2019; United Nations Development Goals, 2015).

Due to the abovementioned controversial issues, over the last few decades, the idea of a Water-Energy-Food (WEF) system has spread globally as a result of the excessive use of natural resources (Allouche et al. n.d.; Benson et al. n.d.; White et al. 2017). A substantial body of literature identifies significant correlations among WEF resources, underscoring the high degree of interdependence between these sectors (De Strasser et al. 2016; Mooren et al. 2024). In the contemporary literature review, the ecosystem pillar has been incorporated in the WEF system; therefore, the WEF approach has been reformulated to the Water-Energy-Food-Ecosystem (WEFE) Nexus approach (Bidoglio et al. 2019; De Strasser et al. 2016; Malagó et al. 2021). Qin et al. (2022) highlight the vital role of water, energy, food, and ecosystems in promoting sustainable conscience, enhancing quality living conditions, and decreasing economic instability. All four pillars of the WEFE nexus are equal and contribute adequately to managing natural resources, which have been depleted due to their overuse (Avellán et al. 2017; Benson et al., n.d.; Chenoweth And Al-Masri 2021; van den Heuvel et al. 2020). The WEFE Nexus approach provides a strategic framework for achieving sustainability in agriculture, promoting the integration of resource conservation with efficient agricultural productivity, rather than focusing solely on high crop yields without sustainable awareness, as was done in past agricultural methods (Pan et al. 2025).

In addition, the WEFE Nexus approach has recently considered biophysical and socio-economic parameters to comprehensively assess the water, energy, food, and ecosystem relationships (Correa-Cano et al. 2022). Traditional agricultural policies often focused on maximizing short-term productivity without adequately considering the long-term consequences on resource depletion, environmental degradation, and economic stability (Feng et al. 2023; Pe'er et al. 2020). This fragmented approach has led to inefficiencies in water use, excessive energy consumption, and soil degradation, highlighting the urgent need for integrated solutions that balance economic viability with environmental sustainability. Given the intricate interdependencies between natural systems and human activity, an integrated assessment of all resource sectors, rather than an isolated focus on individual components, is indispensable for a representative analysis of climate policy. Such a holistic perspective facilitates the identification of future pathways that align economic objectives with environmental resilience and overall sustainability (Palatnik And Roson 2012).

This study elaborates on bioeconomic models, defined as tools that integrate biophysical processes with economic decision-making, with a specific focus on Computable General Equilibrium (CGE) modelling approach, as a response to the issues posed by climate change (Wei And Aaheim 2023). While the broader category of bioeconomic models often focuses on sector-specific or farm-level interactions, CGE models are uniquely designed to stimulate the economy-wide impacts of technological advancements, environmental strategies, and market shocks (Zidouemba et al. 2025). This makes them particularly appropriate for assessing agricultural systems within the integrated framework of sustainability and climate change. CGE models provide a robust framework essential for evaluating nuanced policy initiatives, including carbon taxes, land use allocation, and climate-smart agricultural investments, while accounting for feedback loops across sectors, agents, and markets (Fabregat-Aibar et al. 2022). Their employment in agricultural and environmental economics is gaining interest lately, since CGE models enhance the transition to sustainable agricultural systems, which is the key topic studied. The CGE modelling implementation is a useful tool for the conduction of this Systematic Literature Review (SLR), and as analyzed below, its potential surpasses any other bioeconomic model within the agricultural sector, which is confronting climate change-induced challenges.

Recognizing the complexity of these sectoral feedback loops and economy-wide interactions, researchers and policymakers have increasingly turned to advanced modelling techniques to evaluate the multifaceted impacts of agricultural practices on sustainability. In this context, bio-economic models have emerged as essential tools for

assessing the interconnection among economic decision-making, resource management, and environmental sustainability in agricultural systems (Castro And Lechthaler 2022; Grouiez et al. 2023). More specifically, these models are widely used for the evaluation of the economic, environmental and agricultural production effects of climate change impacts, including the International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) model, the Environmental Policy Integrated Climate (EPIC) model, the Integrated Model to Assess the Global Environment (IMAGE) model and the Trade-Off Analysis Model for Multi-Dimensional Impact Assessment (TOA-MD) model. These models have limitations in terms of accuracy and effectiveness, and they fail to provide a holistic sustainability assessment (Llorente And Luna 2016). Some representative and major reasons for the rejection of the above-mentioned bio-economic models are gained through the detailed review of the available literature and are shortly described below. Firstly, the EPIC model is characterized by inefficient integration of the WEF E Nexus, as it does not offer a holistic analysis of energy consumption in agriculture. This leads to inaccurate assessment of water, energy, food, and environment management (Choruma et al. 2022). On the other hand, the IMAGE model does not consider economic optimization approaches and fails to incorporate market responses, price mechanisms, or trade feedback impacts, hence constraining its capacity to evaluate agricultural economic sustainability. Furthermore, this model is not efficient in crop management and farm-level decision-making (Sacchi et al. 2022). In addition, the TOA-MD model lacks a macroeconomic view and a dynamic evaluation in the long-term, using comparative static analysis for the extraction of results. This model does not consider agricultural technological innovations or adaptive strategies that affect agriculture's resilience to climate change, making it particularly unusable (Hathie et al. 2022). Lastly, the IMPACT model, as it is a partial equilibrium model, does not incorporate economy-wide consequences, intersectoral connections, or long-term dynamic feedback responses, limiting in a wide range its efficacy in the evaluation of agriculture's contribution to sustainable development and climate change adaptability (Sun et al. 2021).

In contrast, CGE models represent a sophisticated subset of the bioeconomic framework (Partridge And Rickman 2010). While the aforementioned traditional bioeconomic models may prioritize high-resolution biophysical data, CGE models are distinguished by their economy-wide scope. They function as a comprehensive bioeconomic simulators by linking agricultural productivity shocks directly to macroeconomic indicators, such as Gross Domestic Product (GDP), household income, and international trade, thereby capturing the indirect feedback loops that simpler

bioeconomic models often neglect (Babatunde et al. 2017). The implementation of the CGE model is required for a thorough assessment of climate change mitigation and adaptation solutions since they surpass the limitations of other bioeconomic tools. Unlike partial equilibrium or sector-specific bioeconomic models (such as EPIC or IMPACT) that lack intersectoral feedback, CGE models provide a holistic framework that encompasses economic, environmental, and social impacts of induced climate change (Kinkpe et al. 2024). These perspectives make the CGE models an integral tool for assessing agricultural policies, trade, and climate mitigation measures. In addition, by integrating agriculture with industry, energy, and services, CGE models can internalize the indirect effects of climate variables, such as temperature shifts and precipitation variations, across the entire macroeconomic landscape (Hossain And Delin 2022). The study of (Partridge and Rickman 2010) indicates that these holistic models encompass the entire economy, integrating agriculture, industry, the energy generation sector, and services to evaluate the implications of climate change among various fields. In addition, CGE models incorporate all climate variables in their equations, including precipitation variations, temperature shifts, and soil classification, thereby providing effective adaptive methods for climate-induced impacts. These models facilitate the promotion of sustainable development by effectively evaluating the interconnections among water, energy, food, and environmental resources, along with the maintenance and protection of these valuable elements (Shahriari et al. 2023). A notable addition to the aforementioned perspectives in the CGE models is that they offer long-term projections regarding agricultural productivity and yields, adaptation solutions and sustainable agricultural strategies. It also underscores the major contribution of CGE models to the assessment of trade and policy implications, including carbon taxation systems, subsidies, and agricultural trade policies (Hu et al. 2021). Results from the study of Ochuodho et al. (2016), highlight the vitality of simultaneously assessing multiple sectors, when employing CGE models to evaluate economic factors. Lastly, these bio-economic models differentiate their measurements among various regions; thereby, they can accurately analyze the climate change-induced impacts among different regions (An et al. 2023). These outcomes make the CGE models useful tools for the agricultural economic sector, ensuring accuracy and sustainability in long-term effects. Consequently, CGE models have been extensively employed to simulate the economy-wide impact of climate change mitigation policies, as well as assess the WEF E Nexus, due to their ability to internalize cross-sectoral externalities within a unified framework (Babatunde et al. 2017).

Delving into the CGE methodological framework, an effective shift from theoretical scope to practical implementation is introduced, taking into consideration economic outcomes of environmental policies (Ji et al. 2022). CGE models are a class of economic tools that use actual economic data to estimate how an economy might react to changes in policy, technology, or external shocks (An et al. 2023). This methodology is built upon a system of non-linear equations that describe the behavior of all economic agents, including households, firms, and the government, across all markets simultaneously. The core theoretical structure of CGE modeling relies on several foundational components to simulate complex agricultural and environmental shifts (Javadi et al. 2023). Rooted in the Walrasian general equilibrium theory, CGE models formalize the interactions between various economic agents, such as households, firms, and the government, across multiple markets simultaneously. According to Dixon and Jorgenson (2013), the strength of the CGE framework lies in its “whole-economy” perspective, which accounts for feedback loops and resource constraints that partial equilibrium models often overlook. By employing a system of non-linear equations to link supply and demand through price adjustments, CGE methodology allows researchers to quantify the systemic impacts of shocks, making it a standard tool for analyzing trade agreements, tax reforms, and environmental policies (“Regulations in a CGE Model,” 2021). The primary data source for calibrating CGE models is the Social Accounting Matrix (SAM). A SAM provides a comprehensive benchmark of the economy for a base year, recording the transactions between sectors and agents (Mbanda And Bonga-Bonga 2024). This allows researchers to establish a static baseline from which dynamic counterfactual scenarios, such as climate-induced yield fluctuations or carbon taxes, can be projected over time. Furthermore, the methodology can be applied at a single-region level for localized policy analysis or via multi-region frameworks to capture global supply chain interactions (Ferrari et al. 2022). CGE methodology is uniquely adjusted to sustainability research as it has the ability to integrate biophysical variables, such as precipitation shifts and temperature variations, directly into economic equations. This allows for the evaluation of the long-term impacts of mitigation strategies (e.g., Greenhouse gas (GHG) reduction, carbon pricing) on social welfare and food security, ensuring that environmental costs are precisely reflected in market dynamics (Böhringer 2004).

The literature review of Fabregat-Aibar et al. (2022) provides key details and data about the CGE implementation in the sight of sustainability, focusing on environmental aspects; thus, it lacks validity regarding the incorporation of the economic and social dimensions. Another review paper by Wei & Aaheim (2023) highlights that autonomous

adaptation embodied in CGE models leads to climate change-induced impact reduction. Furthermore, Wei and Aaheim (2023) demonstrate that CGE modelling in the agricultural sector facilitates the development of adaptation and mitigation strategies, alongside climate-resilient management frameworks. Consequently, these models represent essential tools for addressing the impacts of climate change. On the other hand, Wang and Countryman (2025) conduct research using CGE models to assess the environmental and economic impacts in the context of major global and regional shipping industries and in various geographical scopes and levy rates; yet the social aspect of the results was absent. Furthermore, a CGE model was employed by Yeshineh and Bekele Woldeyes (2025) to determine the economic impacts and human capital development, not considering the environmental and social aspects of the model’s implementation. Dhar (2025) underscores the robust interlinkage between climate adaptation strategies and the WEF Nexus pillars, as well as the enhancement of resilience and effectiveness regarding the transition toward sustainability. It is important to note that only a small number of review articles exist relevant to the Dynamic Agricultural Household Bio-economic Simulator (DAHBSIM) model; thus, further research is necessary to evaluate its implementation. The current study provides a comprehensive evaluation of the 3 main sectors of the economy, the environment, and the society after the implementation of CGE models to assess the climate change-induced impacts mainly on the agricultural sector. The CGE modelling offers more accurate and validated results by considering the 3 aforementioned sectors in estimating the climate change-induced consequences. The inclusion of climate change impacts in this study is an interesting addition regarding CGE modelling implementation. Furthermore, this study incorporates the WEF Nexus pillars to assess the efficacy of sustainability implementation. The aforementioned limitations that have been identified, specifically the frequent omission of social dimensions or the lack of balanced integration between economic and environmental sectors, provide the rationale for the following research inquiries. This study first seeks to identify the scientific methodological gaps and data acquisition strategies currently employed in the field to establish a baseline for CGE implementation. By synthesizing these approaches, the current study evaluates the primary outcomes of CGE modelling across the integrated pillars of the economy, environment, and society, particularly within the agricultural sector. Finally, this study investigates potential pathways to improve the efficiency and accuracy of climate change mitigation strategies by integrating WEF Nexus into CGE modeling frameworks. Ultimately, these inquiries aim to provide a comprehensive scientific roadmap that

addresses the identified shortcomings in agricultural sustainability modelling.

To address the complexities of CGE implementation in the agricultural sector, this study employs a SLR framework following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. This approach achieves its objectives by identifying, screening, and synthesizing 115 relevant articles to evaluate how bio-economic models integrate sustainability and the WEFE Nexus. By applying 30 defined criteria across 8 thematic categories, the methodology provides a structured evaluation of current modelling strengths and identifies specific gaps that necessitate alternative enhancement tools. This systematic synthesis serves as the foundation for the study's contributions to the academic field. The remainder of the paper is organized to reflect this analytical process: Sect. 2 details the SLR methodology and data acquisition; Sect. 3 presents the results and criteria analysis; Sect. 4 discusses the identified research gaps and future scientific pathways; Sect. 5 provides concluding remarks and policy implication.

2 Methodology

2.1 Preliminary

The complexity of assessing bioeconomic CGE implementation in agriculture requires a comprehensive and robust methodological approach that ensures validity, transparency, and repeatability (Liberati 2009). This study employs a SLR, a methodological framework characterized by its dedication to a rigidly precise protocol that facilitates the evaluation of relevant research while mitigating bias (Moher 2009; Xiao & Watson, 2019). By adopting PRISMA guidelines, this study follows a structured context composed of 4 stages, *i*) identification, *ii*) screening, *iii*) eligibility, and *iv*) inclusion, to guarantee transparency and accuracy (Hiebl 2023; Page et al. 2021). Based on the study of Sarkis-Onofre et al. (2021) regarding the importance of PRISMA guidelines, this robust approach is essential for identifying research gaps and evaluating the intricate interconnections within the WEFE Nexus and the associated socio-economic factors emerging from CGE modelling performance.

2.2 Methodology applied

The Scopus and Web of Science (WoS) databases were used, which are distinguished by their extensive coverage of various subjects, excellent quality contents, and relevance to scientific studies. Combining the terms “CGE” or “Computable General Equilibrium”, and “agriculture” aims to identify the most important clusters. Using these

terms, a total of 9,673 results emerged, 4,553 from Scopus and 5,120 from WoS. To determine the final study terms, the previously described results were transferred and subsequently entered into the VOS Viewer software (Waltman & Ecken, 2010). The results of the VOS Viewer program are illustrated in Fig. 1, which depicts five separate clusters: climate change, agriculture, computable general equilibrium, economic analysis, and land use. Consequently, to enhance the outcomes of the current study, the term “climate change” was incorporated into the survey, given its classification in a distinct cluster. The reason why “sustainability” and “sustainable” were excluded as search terms in the final query was based on the analysis performed via VOSviewer. More precisely, the term “sustainability” does not form an independent cluster; rather, it appears as a secondary node deeply embedded within the “climate change” and “agriculture” clusters. This high degree of proximity and nodal interconnection indicates that the term ‘climate change’ serves as a broader, more inclusive keyword that effectively encapsulates the sustainability discourse within the CGE literature. Adding “sustainability” as a mandatory keyword would have risked over-restricting the search and potentially excluding critical CGE studies that address agricultural sustainability through climate-specific variables without explicitly using the keyword “sustainability” in their metadata. In light of these considerations, the final terms used for the queries are “CGE” OR “Computable General Equilibrium”, “Agriculture” and “Climate change”. Title, abstract, or keywords were the primary domains in which these terms should be contained for incorporation in this research.

The outcome of this search leads to a total number of 255 articles and conference papers, with 109 from WoS and 146 from Scopus databases (Fig. 2). The initial screening was conducted to remove duplicates and elucidate the substance of the selected publications. Out of the 164 exclusive documents, 33 were removed in the initial phase because 28 papers were not relevant to the objective of this literature review (these articles did not have any contribution to the present study), 1 was a non-English paper, and 4 of them were not available as full texts. It is important to highlight that the 28 exclusions (i.e., the 28 papers that were removed as non-relevant to the specific objectives of this study) primarily fell into 3 categories, including *i*) papers that employed CGE models for general macroeconomic policy (e.g., urban transport or labor market reforms) without a dedicated focus on agricultural productivity or climate-induced shocks (7 papers), *ii*) papers that used partial equilibrium or purely biophysical models without economy-wide integration characteristic of CGE frameworks (18 papers), and *iii*) papers that focused on historical agricultural data or short-term market fluctuations without addressing the long-term

sustainability pillars or the WEGE Nexus (3 papers). During the eligibility stage, 16 papers were removed, since 11 of them were reviewed articles and 5 of them were excluded due to their low-quality content. The main reasons that these 5 papers were removed from the present study is that (i) 2 of them did not undergo a formal peer-review process, (ii) 2 papers lacked sufficient bibliographical information, and (iii) 1 of them failed to align its economic outputs with biophysical climate variables. Additionally, in the eligibility phase, papers were rigorously assessed against 30 defined criteria (Appendix A) and 8 thematic areas to ensure only high-quality, relevant studies were included in the final synthesis. According to the aforementioned procedure, 115 papers were incorporated into this SLR. Of the total number of papers assessed for this review, 111 were journal articles, making up 96.6% of the overall; 3 were book chapters, and 1 was a conference paper, accounting for 3.4% of both of them. Ultimately, the final timeframe that emerged for this study is the search period from 2009 to 2024. This range of years in which the search was carried out provides a comprehensive analysis of the field's transition from traditional productivity-focused CGE models to CGE model frameworks that integrate the WEF Nexus variables, as well as SDGs. The final search queries from the Scopus databases is TITLE-ABS-KEY (cge OR computable AND general AND equilibrium) AND TITLE-ABS-KEY (agriculture) AND TITLE-ABS-KEY (climate AND change) AND PUBYEAR>2008 AND PUBYEAR<2025 and for WoS database is (TI=(CGE)) OR AB=(CGE) OR AK=(CGE)) AND ((TI=(agriculture)) OR AK=(agriculture) OR AB=(agriculture)) and (TI=(climate change) OR AK=(climate change) OR AB=(climate change)) AND PY=(2009–2024), respectively. This systematic search was conducted on January 27, 2025, covering the publication period from January 2009 to December 2024; thus, capturing the evolution of CGE modeling from early agricultural assessments to the modern WEF Nexus framework.

3 Results

The purpose of this study is to enhance the knowledge of bio-economic models in agriculture under the prism of sustainability, emphasizing on the CGE model and its effect on environmental, economic and social level. Eight thematic categories have been determined through the procedure of the evaluation of the reviewed articles, and they conclude various cases of the implementation of the CGE models. These categories are general information, field information, WEF Nexus approach classification, impacts of climate change, relations to international initiatives and goals, CGE

models, climate change mitigation measures, sustainability impacts of model implementation, as illustrated in Fig. 3.

In addition, an extensive criteria table was developed before the thorough assessment of each paper. Appendix A indicates some representative criteria that were assessed in each paper. The purpose of the criteria was to depict the comprehensive implementation of the CGE model in the agricultural sector under the prism of sustainability, as well as identifying fields requiring enhancement or improved integrated approaches from different areas of science.

3.1 General information

In this category, four primary criteria are examined: (i) the publication year, (ii) the publishing company, (iii) the source type, and (iv) the document type. Regarding the “document type”, of the total reviewed documents, only one is a conference paper, and three are book chapters, while the rest of them are journal articles (111). As is illustrated in Figs. 4 and 2019 is the year with the most article publications (12), followed by the year 2023 (11).

Regarding the publisher data, as shown in Fig. 5, the most widely used publishing companies among the reviewed articles are Elsevier and other publishing companies (23), as well as Springer (22). It is important to mention that the category “Other” includes publishers with fewer than 2 articles.

Furthermore, the documents are categorized according to their source type. Out of the total documents, 13% of them are obtained through WoS and the rest of them (87%) through Scopus database.

The assessment of document types, publishers, source type and the publication year serves to establish the methodological quality of the synthesized literature, ensuring that the findings are predominantly derived from high-impact, peer-reviewed journal articles rather than grey literature with a view to the years of publication.

3.2 Field information

Regarding the “Field information” category, it concludes three main criteria which are examined thoroughly below: (i) country, (ii) sector, and (iii) crop type. It is essential to consider the countries in which the examined documents of the present study have been published, as they differ in meteorological conditions, crop cultivation and input types. As illustrated in Fig. 6, a significant portion of the examined documents focuses on China (8%), followed by Ethiopia (4%) and Brazil (4%). The concentration of research in China is largely driven by national mandates to achieve “dual carbon” goals and the commitment to reduce carbon emissions relative to GDP by 60–65% by 2030 (Hong et

Fig. 3 Thematic categories of the reviewed articles

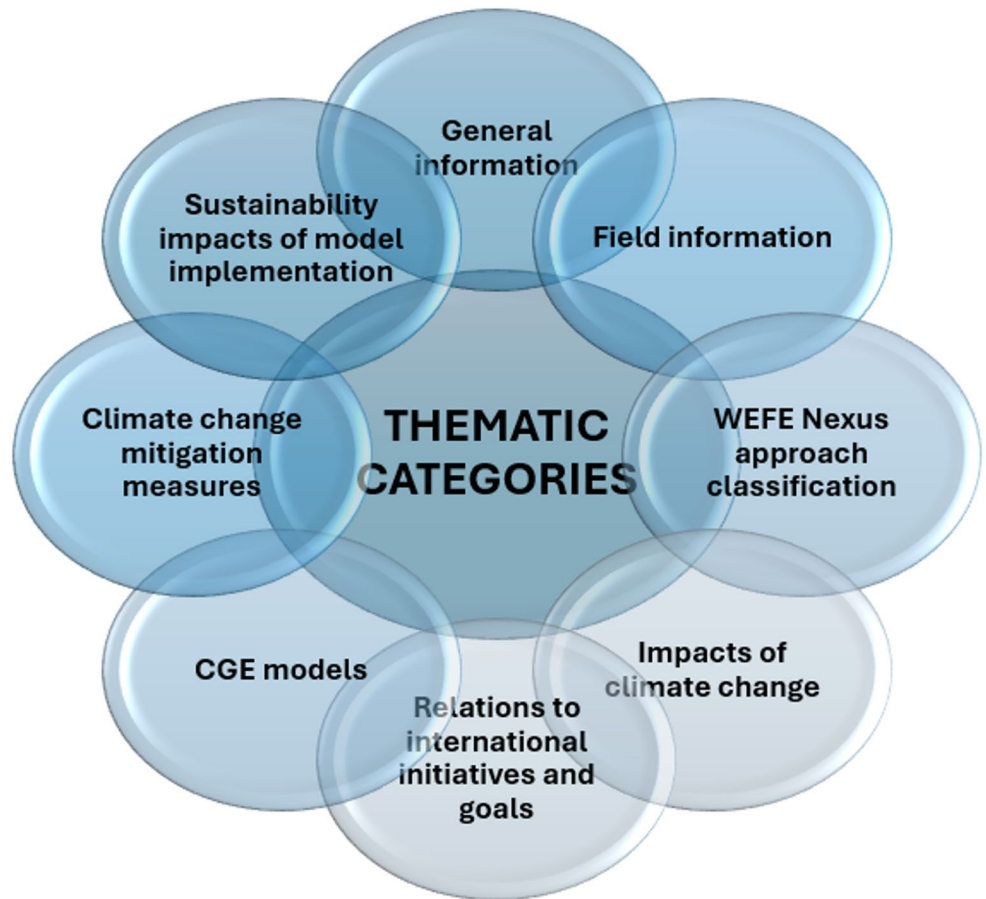
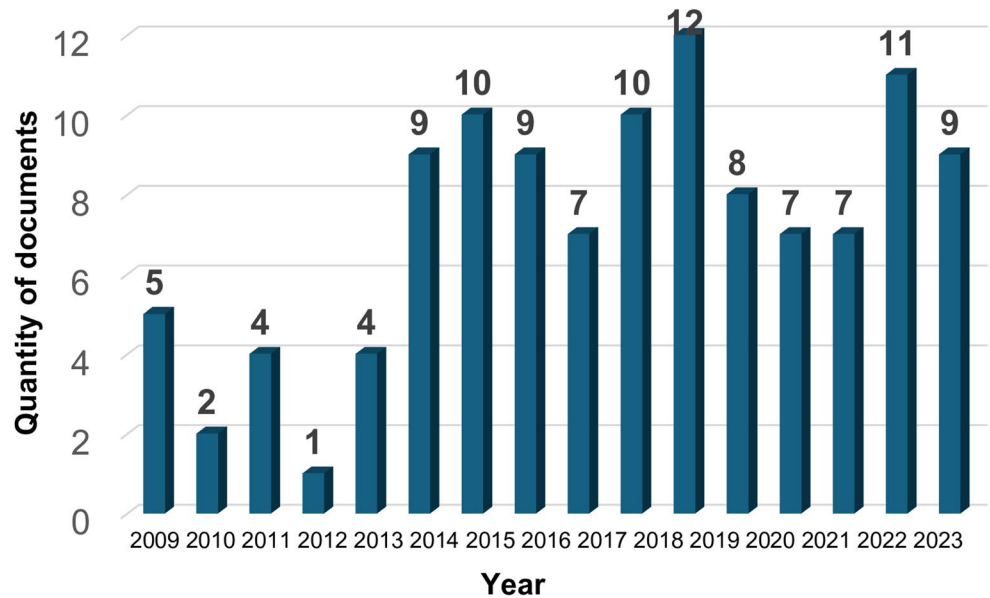


Fig. 4 Quantity of published articles per year from the reviewed articles of the present study



al. 2024; Mehmood et al. 2024). Similarly, in Ethiopia and Brazil, the adoption of CGE models is necessitated by the urgent need to evaluate climate-resilient adaptation strategies in sectors that are vital to their national economies but highly vulnerable to precipitation and temperature shifts.

CGE models are more appropriate because they link agricultural shocks directly to macroeconomic indicators like GDP and household income, which are more volatile in these economies (Devarajan And Robinson 2013). It has to be outlined that the countries named “Others” are those

Fig. 5 Number of articles per publishing company from the reviewed articles of the present study

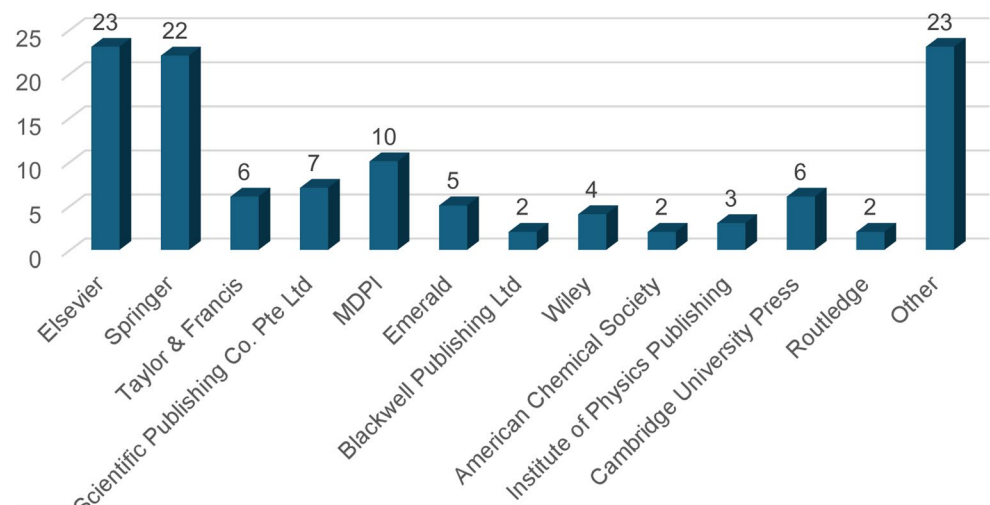
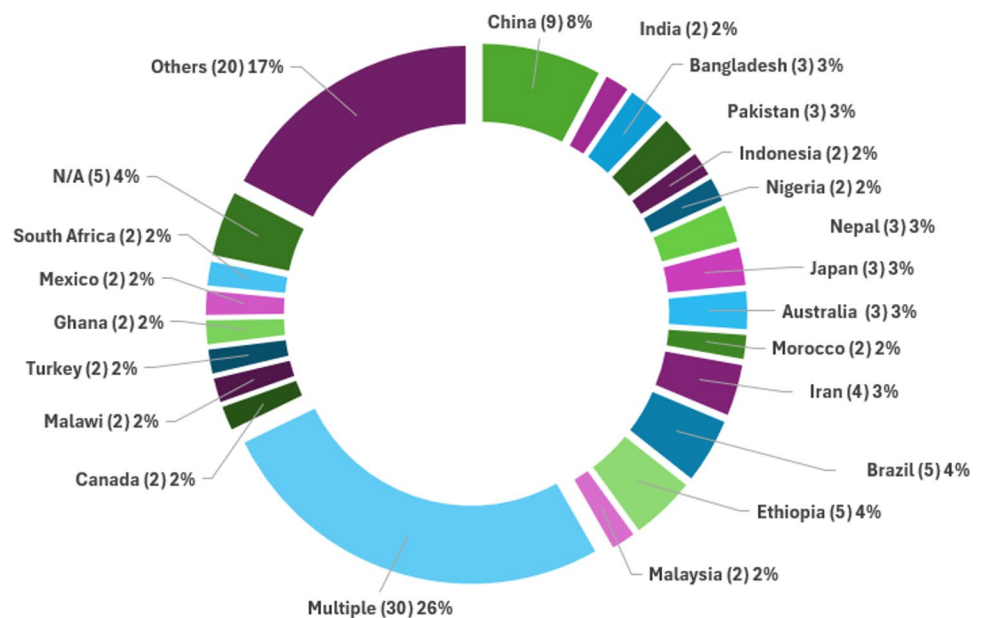


Fig. 6 Countries of the reviewed studies



which have conducted only one research relevant to the examined subject of the present study. Furthermore, the studies in which the examined countries are not available are included in the “N/A” countries. The studies that include more than two examined countries, are part of the “Multiple” countries, which obtain an important percent out of the total countries (26%).

Figure 7 illustrates the countries in which the examined documents have taken place, including those with only one study relevant to the subject examined in the present study. These countries are Gambia, Kuwait, Benin, Israel, Burkina Faso, Sri Lanka, Switzerland, Mali, Netherlands, Philippines, New Zealand, Mozambique, Guatemala, Ireland, Austria, Sudan, Zhangye, Poland and Costa Rica. In the European Union (EU), while it is identified a strong relation to EU goals such as the Farm to Fork Strategy and CAP 2023-27, the lower frequency of domestic CGE-specific

studies may suggest that EU researchers often favor sector-specific Partial Equilibrium (PE) models for local compliance due to their higher commodity resolution. CGE models remain the primary tools to evaluate the global implications of EU trade policies like the Carbon Border Adjustment Mechanism (CBAM) (Weitzel et al. 2024). The prevalence of studies in European nations, such as Poland, the Netherlands, Austria, and Ireland, reflects the direct influence of regional policy frameworks. For instance, research in Poland has utilized CGE frameworks specifically to assess the pathway toward climate neutrality by 2050, demonstrating how regional legislation acts as primary catalyst for methodological adoption (Anagnostou et al. 2023). It is notable to mention that countries with quite important agricultural sectors on a global scale appear not to have relative studies, like the USA, Argentina, Germany, France Denmark, etc.

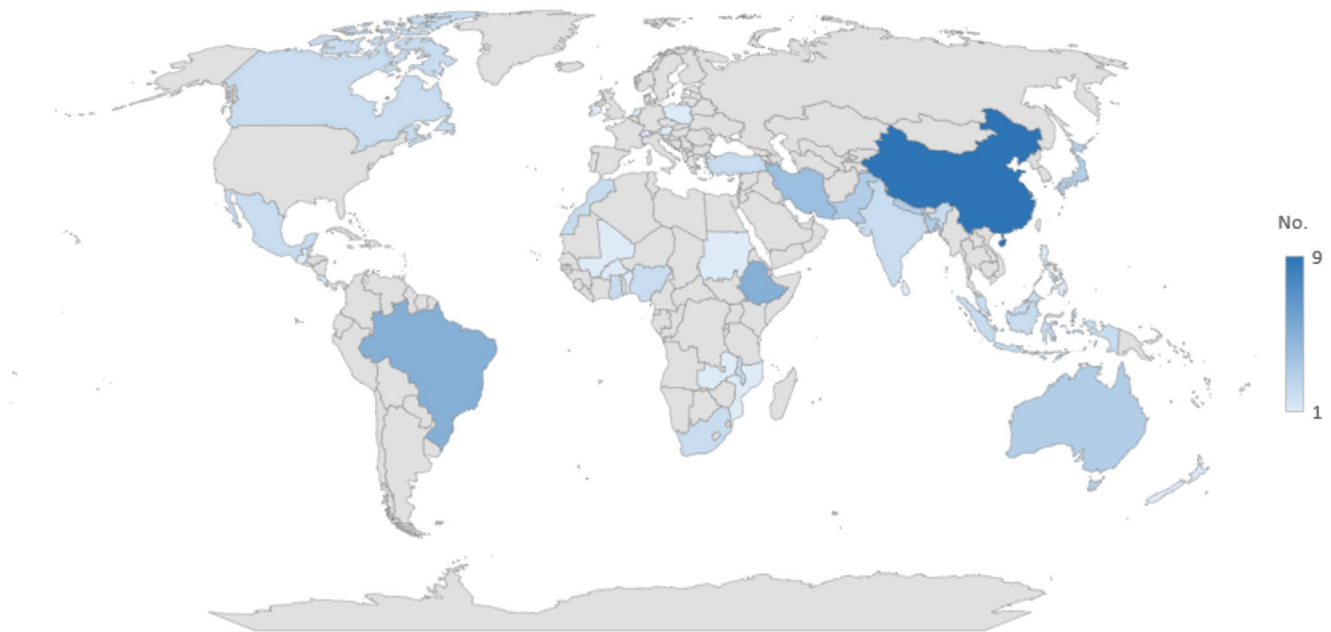


Fig. 7 Map of the countries included in the examined documents

The observed geographical distribution reveals a notable research gap: while major agricultural exporters such as the USA, Argentina, and several EU member states possess highly developed agricultural sectors and robust sustainability frameworks, they are underrepresented as primary subjects in CGE-based sustainability papers. This may be attributed to the fact that researchers in these regions often employ Partial Equilibrium (PE) models (e.g., CAPRI for the EU) for sector-specific policy analysis, which offer higher commodity resolution but lack the economy-wide feedback loops of CGE models (Latta et al. 2013). Consequently, although the reviewed literature frequently aligns with EU initiatives, such as the Farm to Fork Strategy and CAP 2023-27 (as detailed in Supplementary Table 5), these goals are often used as external benchmarks to evaluate impacts in developing nations rather than as the primary focus of national CGE assessments within Europe itself.

Concerning the sectors in which the reviewed articles are conducted, it is found that the agricultural and the services sectors are at the top of the academic research discipline. This indicates their crucial role across all economic sectors, as any potential recession will have a considerable negative impact on agricultural sector feasibility, affecting also productivity, crop yields, food security and availability, social welfare and sustainable agricultural practices.

Regarding the crop types that are mostly studied in the reviewed articles, maize, rice and wheat gain interest both in the bioeconomic models' implementation and the assessment of their impacts in light of climate change. Indicatively, (Komarek et al. 2019) refer to the fact that the adverse implications of climate change will result in productivity

and yield reduction of these crops, since excessive temperature and precipitation fluctuations may occur.

The identification of specific geographical concentrations, critical economic sectors, and essential crop types in this section establishes the foundational landscape for current CGE research. However, the high vulnerability of these sectors and regions, particularly regarding staple crops like maize, rice, and wheat, demands a move beyond isolated sectoral analysis toward a more integrated resource management framework. This transition from individual field information to holistic systems thinking is best captured through the WEF Nexus approach. While this section defined the spatial and sectoral boundaries of the literature, the following section classifies how these studies internalize the intricate interdependencies between resources to address the multifaceted sustainability challenges inherent in modern agri-food systems.

3.3 WEF Nexus approach classification

The WEF Nexus is a system that describes the interconnection between water, energy, food, and environment and underlines the high dependence among these terms (Halystia et al. 2024). Recently, the WEF Nexus has been a vital issue of concern for many scientists, as it is closely related to the SDGs by the United Nations (UN). Adopting a WEF Nexus strategy enhances synergistic approaches and addresses trade-offs among the WEF components, while also revealing the intricate interconnections among its elements and the involvement of various types of sectors in the WEF initiative (Özcan et al. 2024). The current

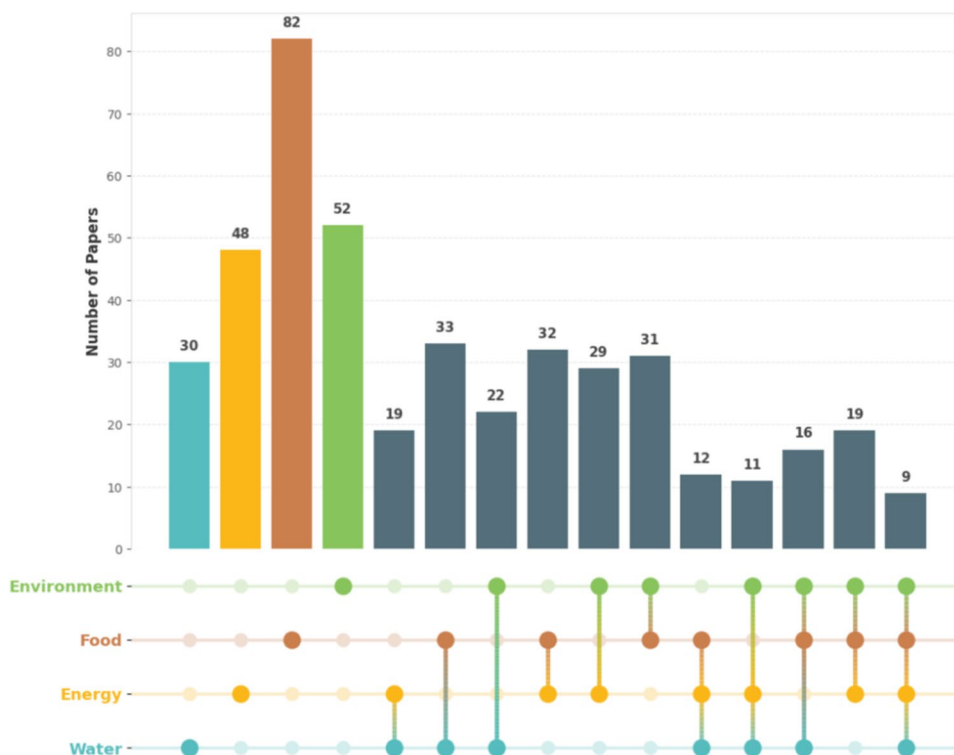
study pays close attention to the category “WEFE Nexus approach” and analyzes its four main criteria: (i) water, (ii) energy, (iii) food, (iv) environment, which are extensively analyzed in Supplementary Table 2 (Appendix A). Furthermore, the intersectoral linkages and interaction analysis among the WEFE elements is presented to ensure a more comprehensive perspective of WEFE evaluation. Moving beyond a siloed sectoral perspective, the analysis of resource interdependencies reveals the depth of the Nexus implementation in current CGE literature. Figure 8 depicts the number of the examined documents in which each of the aforementioned 4 criteria is included alongside the interconnections among the WEFE elements. It is evident that the larger amount of the reviewed studies examine the factor “food security” (82), followed by “environmental protection” (52). Afterwards, “energy generation” (48) and “water management” (30) follow. With respect to the intersectoral linkages and interaction analysis (Supplementary Table 3), among bilateral interconnections, the Water-Food Nexus is the most predominantly examined, appearing in 33 of the analyzed articles. This high frequency reflects the central role of water allocation and irrigation efficacy in determining agricultural productivity and food availability under climate stress. Regarding trilateral interconnections, the Food-Energy-Environment interaction is the most frequently referred to (19 articles), highlighting a growing focus on the complex trade-offs between renewable energy expansion, agricultural outputs, and environmental conservation targets. Finally, the most sophisticated level of full

Nexus integration is achieved in 9 articles, which concurrently internalize all four WEFE elements within a unified economy-wide framework. These studies provide the most comprehensive assessments of the multi-dimensional trade-offs required to satisfy the SDGs and long-term agricultural resilience. These bilateral links show that CGE models are ideal for measuring how a change in one resource affects the entire WEFE system.

3.3.1 Water management

It is widely recognized that natural resources will face significant negative, and in some cases, destructive, impacts over the coming decades due to climate change, particularly in regions with fragile environmental balances (Amiri et al. 2021). These consequences will affect various sectors, with agriculture experiencing the most intense repercussions (Yeboah et al. 2023). (Karthé et al. 2025) highlight that water and climate change are strongly interlinked; therefore, water security depends significantly on the effective management of climate-induced impacts. More precisely, the depletion of water resources is one of the most detrimental consequences of the excessive water use combined with rising global temperature (Amiri et al. 2021). For this reason, it is imperative to enhance water use efficiency and implement advanced irrigation systems to achieve optimized water management (Tang et al. 2005; Tennakoon And Milroy 2003). According to (Khan et al. 2020), establishing appropriate infrastructures and utilizing technological

Fig. 8 Distribution and intersectoral interconnections of Water, Energy, Food, and Environment (WEFE) Nexus pillars in the reviewed articles



equipment are vital to reducing water loss and overcoming challenges posed by extreme climate events. In addition, (Hou et al. 2007) emphasize that nations must strictly adhere to Irrigation Water Management (FAO, 2025) guidelines to enhance sustainability of irrigation practices and improve crop yields.

The assessment of international literature has identified various measures to mitigate climate change repercussions and minimize water scarcity. Numerous studies have estimated agricultural water consumption and developed improved management solutions. For instance, Guo et al. (2020) state that the agriculture sector demands approximately 60% of the national water needs, estimating the water footprint through comprehensive input-output tables. Their research suggests that water-saving irrigation technologies, the rational distribution of available water sources, and the use of resilient crop varieties are essential for optimizing water management. Another study by (Komarek et al. 2019) examines different technological methods for maize and wheat cultivation to adapt various innovative strategies for saving water supplies. Indicatively, these methods include the monitoring of soil moisture and plant water deficiencies. Ultimately, efficient water management preserves natural resources, promotes sustainability, and mitigates water scarcity (Coskun Dilcan And Aydinalp Koksak 2025). (Lv et al. 2025) conclude that optimizing water management is an effective approach to fostering resource preservation and preventing water shortages; thus, a different range of measures tailored to specific water issues should be implemented.

3.3.2 Energy generation

Energy constitutes the second pivotal element of the WEFE Nexus, and energy conservation has received substantial attention within the scientific community. A significant concern, as noted by Winchester and White (2022), is the need to utilize energy sources more efficiently while considering the environmental impacts of increased energy consumption. Agriculture is a prominent energy-consuming sector; for example, (Ngoma et al. 2021) found that approximately 63% of Zambia's energy needs are derived from cereal cultivation. The researchers emphasized that the detrimental effects of climate change on energy have immediate consequences for agriculture production. The use of non-renewable energy sources, including coal, oil and petroleum, results in the release of CO₂ in the atmosphere, exacerbating environmental pollution (Gurgel et al. 2019). Findings from Gurgel et al. (2019) and Pradhan and Ghosh (2019) highlight that substituting fossil fuels (primarily coal) with alternative energy sources, such as solar, wind energy, and hydropower, contributes to mitigating resource depletion.

Motamedisedeh et al. (2025) point out the economic viability of solar energy and the integration of other renewable energy sources, emphasizing the importance of photovoltaics in optimizing clean energy across all sectors. Photovoltaics also provide co-benefits for water management and food production systems. Aslam et al. (2025) advocate for the adoption of solar power towers as an innovative measure to achieve high-efficiency energy, economic stability and long-term sustainability. In the same line, Bhandari et al. (2025) emphasize that hydropower development mitigates climate impacts while maintaining social stability and environmental integrity. Furthermore, a study of Hahn et al. (2025) evaluates the role of farmers in the transition toward sustainable agriculture and renewable energy systems. Initiatives, such as funding, consultation, and governmental financial support are essential to incentivize farmers to adopt clean energy practices.

The adoption of strategic measures, such as taxes on energy-intensive agricultural production, are necessary to enhance sectoral sustainability (Pradhan And Ghosh 2019). Conversely, implementing subsidies for agricultural practices that use renewable energy sources, as described in the Brazilian Nationally Determined Contribution (NDC), is vital (Gurgel et al. 2019). Many of the reviewed articles examine the results of implementing energy efficiency initiatives, such as carbon taxes, and how these cooperative efforts improve the reduction of GHG emissions (Gurgel et al. 2019). Finally, Gurgel et al. (2019) conclude that the expansion of cropland and the rise in crop production up until 2050, which result in intensive energy consumption as well as an increase in the use of agrochemicals, are increasing further carbon emissions. In summary, to mitigate the negative impacts of energy overuse and non-renewable energy sources, various measures are recommended, including the use of renewable energy sources and their subsidies, as well as the imposition of carbon taxes.

3.3.3 Food safety

Food safety is directly connected to climate change impacts, which increase the vulnerability of food production, cause price fluctuation, and threaten global food security. Cai et al. (2016) state that food insecurity and climate change are two significant threats that the planet is currently confronting, and the adverse effects of climate change on food security will be most severe in countries that are already experiencing poverty. Continued global population growth, coupled with climate deterioration through 2080, is expected to create a significant gap between food supply and demand (Bandara And Cai 2014).

Numerous studies have examined the climate-induced alterations to food security. Indicatively, Bandara and Cai

(2014) assessed changes in food productivity in South Asian countries, concluding that climate change will impact both the production and economic sectors. More precisely, they project that by 2030, the production of rice, wheat and cereal grains could decrease by 4%, 11% and 7%, respectively, leading to substantial price increases. Solaymani (2018) underlines the urgent need for agricultural technological innovations and farmer training workshops to adapt to these challenges. In addition, selecting crop varieties resistant to extreme weather fluctuations is recommended to stabilize food availability (Banerjee et al. 2015). In the same line, Lemaire et al. (2014) emphasize the need to combine modern crop-livestock systems as a response to current challenges and to ensure food security while preserving ecosystem integrity. They also highlight the importance of optimizing food productivity with a view to ecosystem services maintenance, which is a prerequisite for combating climate change effects. In conclusion, ensuring food safety is essential for survival, making it crucial to confront the global challenges resulting in food insecurity.

3.3.4 Environmental protection

In light of environmental consciousness, agriculture is widely accepted as the sector most vulnerable to environmental shifts, which can have profound economic impacts. This necessitates the implementation of strategic mitigation measures tailored to climate change (Nazareth et al. 2022). On the other hand, environmental resources are also threatened by intense agricultural activities, particularly in regions highly dependent on agricultural revenue (Arto et al. 2020). Population growth has also led to the expansion of agricultural activities, leading in environmental degradation and exacerbated climate phenomena (Vatankhah et al. 2020). Wills et al. (2023) underline that countries characterized by a high GDP level and industrial development are more prone to environmental degradation. This aligns with

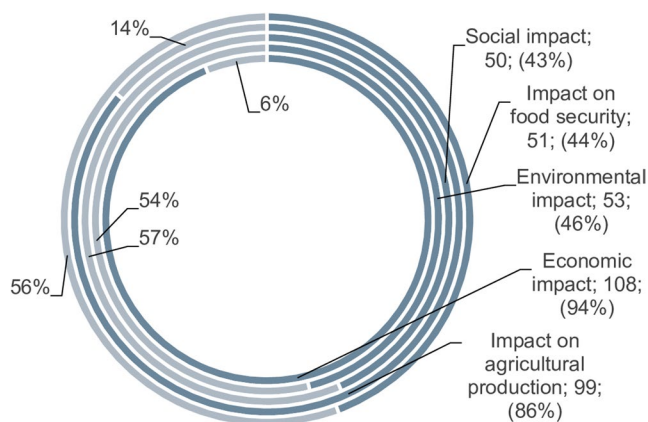


Fig. 9 Impacts of climate change per sector which are included in the examined articles

Sarioğlu's (2025) study, which found that achieving economic and social viability often undermines environmental stability within the context of sustainability. The high content of GHGs in the air harms the entire ecosystem with irreparable consequences, as these gases are released from various sectors, including the industrial sector (Vatankhah et al. 2020).

Many of the examined studies have analyzed the environmental impacts of agricultural expansion and excessive fertilizer use. A central concern for researchers is whether sustainable agricultural methods can simultaneously satisfy environmental protection and increased crop yield. Nevertheless, the maintenance of environmental protection will be beneficial for the entire planet (Nong 2019). Recent efforts have sought to transform agricultural activities that damage the environment into sustainable agricultural systems with the minimum ecological footprint (Pradesha et al. 2022). Cozim-Melges et al. (2025) demonstrate that the implementation of alternative agricultural approaches is beneficial to ecosystem maintenance with a high efficacy in soil biodiversity enhancement. Furthermore, Muhirwa et al. (2025) find that ecological resilience assessment are necessary to mitigate ecosystem damage and promote environmental sustainability. Lastly, Giannetti et al. (2020) introduced the insight of "cleaner production" to protect ecosystems and promote resource efficacy, leading to sustainable motivations.

Summarizing, while the WEF Nexus provides the structural framework necessary to understand the complex interdependencies between natural resources and economic sectors, these systems do not operate in isolation; they are increasingly subjected to external pressures that threaten their stability (Abera et al. 2024). To fully grasp the magnitude of these challenges, it is essential to move from the classification of resource linkages to the evaluation of the specific disturbances that trigger systemic vulnerabilities. Consequently, the following section examines the multifaceted impacts of climate change, detailing how these environmental shocks translate into measurable economic, environmental, social, agricultural, and food security consequences within the reviewed literature.

3.4 Impacts of climate change

Climate change exerts significant effects across numerous sectors. The current study indicates that several studies assess the impacts of climate change across various sectors, highlighting its detrimental repercussions and the imperative for effective mitigation strategies. This category evaluates five primary criteria, as illustrated in Fig. 9: (i) economic impact, (ii) environmental impact, (iii) social impact, (iv) impact on agricultural production, and (v) impact on food security.

The majority of the examined articles (108) evaluate the impacts of climate change on the economic sector, while a lesser number (99) focus on its effects on agricultural production. The environmental impacts of climate change are extensively studied in the reviewed articles (53), while its impacts on food security and society are also considerable, with a number of 51 and 50 articles, respectively.

3.4.1 Economic impact

Economic impact represents one of the most significant consequences of climate change, manifesting through both direct and indirect channels as detailed in the reviewed literature. Because the economy underpins decision-making across all sectors, its stability is vital on both national and global scales. Most of the reviewed studies have estimated the economy-wide impacts of climate change, using different bio-economic models. More precisely, Arndt et al. (2015) conduct a comprehensive study in which they evaluate the severe consequences of climate change to the economic sector, implementing four different climate change scenarios that encompass every aspect of anticipated adjustments to Ghana's humidity indicator. They also observe a GDP loss in the country by the year 2050. In addition, Bachner et al. (2015) conclude that the decrease in the GDP rates in Austria is the result of the adverse consequences of climate change, which come from the electricity, forestry and tourism sectors, and the advantageous outcomes of climate change from the agricultural sector (because of the increased crop yield, which raises the GDP prices). The results of this study, further, highlight the multifactorial nature of climate change impacts on the economy. Another relevant study underlines that climate change mitigation will enhance economic welfare, while climate change exacerbation will have negative impacts on the macroeconomic indicators of the country of Iran (Vatankhah et al. 2020). The researchers also found that the real GDP and the economic growth of Iran will decline due to the rising temperatures and the droughts the country is facing. Lastly, Wąs et al. (2021) underline that the agriculture productivity sector, which is directly dependent on the economic sector, will face the adverse impacts of climate change through the reduction of the production and yield; thus, increasing the prices of the final products and affecting their demand and supply on the production chain. It is evident that the economy will face serious side effects due to climate change, and a lack of mitigation measures will result in economic instability.

3.4.2 Environmental impact

Climate change is recognized as a worldwide and enduring issue that severely damages the environment. Over the past

few decades, several efforts have been made to overcome a variety of challenges, including environmental degradation and unsustainability problems, caused mainly by climate change. For this purpose, many international approaches have been introduced, such as the "Green Economy" from the "Environment Programme (UNEP), to mitigate the environmental deterioration and the resource scarcity and to encourage sustainable economic growth (Yeboah et al. 2023). In addition, SDGs, as they are presented by the UN, are receiving worldwide dissemination and aim to protect the environmental resources by many threats, including the impacts of climate change. Through the detailed assessment of the reviewed articles, it seems that many researchers focus their studies on the maintenance of the environmental resources and the preservation of the sustainable development across different sectors, mainly the environmental sector. A noteworthy ascertainment from Arto et al. (2020) refers to the fact that societies with high dependency on agricultural activities are more susceptible to adverse consequences of climate change. In another study on the environmental impacts of climate change, Zhang et al. (2022) examine the effects of GHG emissions and conclude that reducing these emissions can be achieved by promoting sustainability and biological cultivation schemes in the agricultural sector, which is closely linked to environmental resources. Gong and Huo (2024) assess the effects of four carbon emission mitigation strategies in order to accomplish zero emissions in China's economic system and environment. In this way, the environmental impacts caused by climate change were decreased, and the promotion of sustainable development was extended. Environmental impacts due to climate change severely affect the planet, and immediate measures must be taken to face these challenges and promote sustainable development worldwide.

3.4.3 Social impact

Social impacts due to climate change effects are the least studied criteria over the examined articles; nonetheless, they are a significant climate change-induced challenge, which is affecting many countries worldwide. The decline in agricultural outputs and yields, as a result of climate change, presents challenges on a social scale. This is due to the fact that the agricultural sector employs a significant number of the population, offering decent income and social welfare, especially in the South Asian countries. This phenomenon exacerbates the vulnerability of households with low incomes, as their revenues are based on the deficient natural resources due to climate change, and this results in inadequate social welfare (Chalise et al. 2017). In their study, Hussein et al. (2013) examine the poverty rate among different population groups in 14 developing countries using a comprehensive

climate mitigation approach under different scenarios (e.g., subsidies to promote the storage of carbon in forests, fossil fuel taxes, and taxes that don't contain carbon dioxide emissions). They find that climate change mitigation measures have either an immediate or subsequent effect on poverty. Additionally, a study conducted by Vatankhah et al. (2020) estimates the social welfare impacts of climate change in Nepal, using bioeconomic models that extend to all social, agricultural and economic sectors. A current social fragility that is a result of climate change is the migration due to the search for new opportunities in the urban centers. It is evident that the social sector is adversely affected by climate change, and immediate mitigation measures should be taken to reduce these impacts.

3.4.4 Impact on agricultural production

Agriculture is the second major sector facing the detrimental impacts of climate change, as many studies have been conducted to assess the hazards and implement solutions for the mitigation of this worldwide phenomenon. Agriculture is connected not only to the economic sector, as mentioned above, but also to the food security system, the social welfare system, and the environmental sector. The collapse of the agricultural production system leads to the degradation of other sectors, given their strong interlinkage. The devastating impacts of climate change on agriculture are reflected through the examined studies, and some representative findings are presented below. Agriculture is the cornerstone of Mali's economic prosperity, creating jobs for 75% of the overall population and contributing 41% to the country's GDP (Montaud 2019). The researchers, using a bioeconomic model, assessed the impacts of climate change and, more precisely, the effects of water shortage in the agricultural sector and found that the decrease in crop production results in the reduction of social welfare, as well as a struggle between residents for fresh water. Another study carried out by Zidouemba & Gerard (2018) underlines the repercussions of agriculture productivity degradation due to climate change, which include the rise of agricultural prices, on the society and household food security system. The study elaborates that the poorest households will experience the most severe impacts of agriculture yield reduction. Finally, agricultural production is expected to be severely affected by climate change in the absence of adaptive mitigation measures (Calzadilla et al. 2014). Regarding the above-mentioned studies, it is concluded that the consequences of climate change will severely affect crop productivity, resulting in food insecurity challenges and food price deterioration. In conclusion, according to W. Zhu et al. (2025), the implementation of green production technologies and

practices is required for the mitigation of agricultural vulnerability against climate change-induced impacts.

3.4.5 Impact on food security

Food security is a major issue that concerns the scientific community, as well as the rest of the world. Agriculture and crop productivity are vulnerable to climate change impacts, and any potential decline in their yields leads to food security difficulties. A large number of the studied articles evaluate the climate change effects on food productivity. A comprehensive example of a study conducted by Cai et al. (2016) assesses the implications of climate change on food security using a range of different models. Their results indicate that climate change has substantial adverse effects on food production and prices, despite the possibility for changes to mitigate these effects. The researchers conclude that by 2040 the output of agricultural products in all South Asian countries will decrease as a result of climate change. It is also anticipated that the prices of rice and wheat will increase dramatically, resulting in a decrease in food consumption due to the increased food prices. Another study examines the five Shared Socio-economic Pathways-induced food security effects in Kuwait, and the results indicate that agricultural and food productivity sectors will experience disparate effects in each scenario, with food prices experiencing a high rate of increase in every distinct scenario. Vargas et al. (2018) find that a decrease in agricultural outputs, due to severe droughts in Guatemala, results in food insecurity concerns and, more precisely, an increase in food prices and a decline in food consumption. A noteworthy finding from Diallo & Wouterse (2023) is that expenditures from agricultural activities would substantially enhance agricultural development and crop productivity, decrease dependence on imported food, enhance producers' revenues, and reduce hunger. Solaymani (2018) evaluates the immediate and future implications of potential changes in precipitation and temperature on Malaysia's food productivity and availability, which are two vital components of food security. The findings of the aforementioned study highlight the detrimental effects of weather condition variability on food supply and demand, due to a reduction in agricultural outputs. It is concluded that food security is directly linked to climate change-induced impacts, and any possible collapse of the agricultural sector will lead to food insecurity.

The widespread impacts of climate change across economic, environmental, and social dimensions, alongside agricultural production and food security, highlight the urgent need for coordinated, large-scale interventions to protect global systems. Because these challenges, ranging from GDP loss to severe food insecurity, are too complex for localized solutions alone, they have driven the development

of robust international frameworks and policy benchmarks. The following section explores how the literature aligns these climate-induced pressures with global initiatives, such as the UN SDGs and EU policy mandates, to foster a more resilient and sustainable future.

3.5 Relation to international initiatives and goals

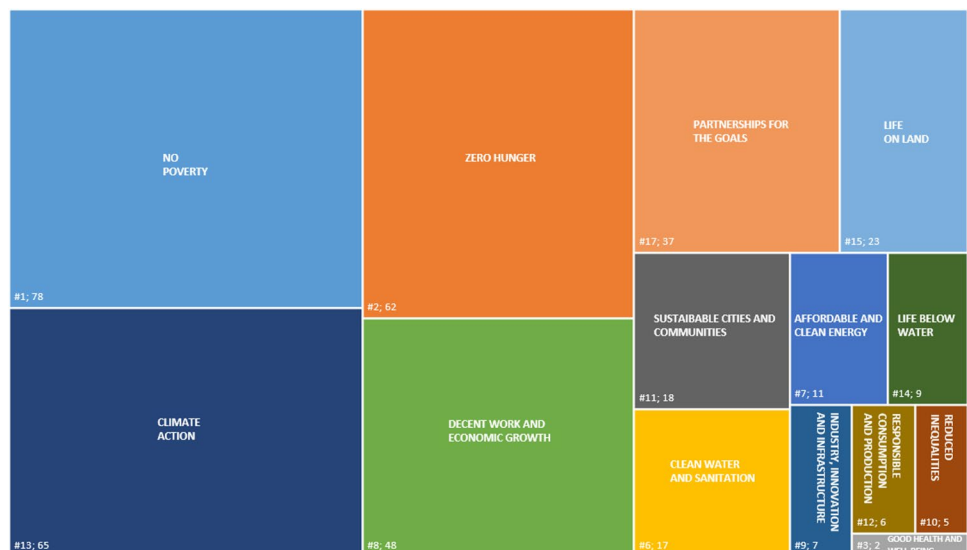
The present category includes and analyzes three main criteria, which are: (i) Relation to SDGs, (ii) Relation to EU goals and (iii) Relation to other goals. For a thorough examination of the aforementioned criteria Supplementary Table 5 indicates information and data. SDGs are gaining significant attention recently and multitude attempts have been made by the UN to implement them at a global level. As illustrated in Fig. 10, in the examined articles 14 out of the 17 SDGs have been identified, and more precisely the number of articles that include each goal are: #1 No poverty (78 articles), #2 Zero hunger (62 articles), #3 Good health and well-being (2 articles), #6 Clean water and sanitation (17 articles), #7 Affordable and clean energy (11 articles), #8 Decent work and economic growth (48 articles), #9 Industry, innovation and infrastructure (7 articles), #10 Reduced inequalities (5 articles), #11 Sustainable cities and communities (18 articles), #12 Responsible consumption and production (6 articles), #13 Climate action (65 articles), #14 Life below water (9 articles), #15 Life on land (23 articles) and #17 Partnership for the goals (37 articles). The #1 goal (No poverty) is the most cited in the examined articles followed by the #13 goal (Climate action) and #2 goal (Zero hunger). Given the significant number of articles that include goals #1, #2, and #13, it is evident that the topics related to climate action measures and the mitigation of malnutrition and impoverishment greatly concerns scientists internationally. And this reasoning is based on

the fact that enhancement of sustainability and ecological consciousness leads to an increase in food availability of 1,7%(Torán-Pereg et al. 2025).

A subject that has been studied extensively in the reviewed articles is poverty and hunger and how these hazardous conditions can be eradicated. According to Chalise and Naranpanawa (2023), land relocation leads to a reduction in income disparities and poverty between residents of the city centers and families in the countryside by minimizing the earning deficits of poor agricultural producers. In addition, since the agricultural sector is the primary source of income for developing countries, it is necessary to implement adaptation measures and policy guidance in a short period of time to address the severe impacts of climate change on the agricultural field. In this way, it is ensured that the incomes from the agricultural activities will remain stable, and the proportion of impoverished households will reduce (Hussein et al., 2013). Furthermore, the climate crisis and its consequences concern a great proportion of the population globally, and in the examined articles, many mitigation measures have been assessed. It is essential to promote the collaboration of all countries and the implementation of climate policy strategies to effectively confront the impact of climate change (Golub et al. 2009). These strategies include carbon taxes, policy measures, and awareness of the population, which are extensively analyzed in subcategory 3. 7.

Through the process of assessing the reviewed articles, a vital type of criteria emerged, which is in relation to EU goals. The EU goals have been classified by their relevance to different sectors. These sectors are water, energy, food, and environment. The water sector includes the below goals: C (2000/60/EC), EU Blueprint to Safeguard Europe’s Water Resources (2012), Floods Directive (2007/60/EC), Urban Wastewater Treatment Directive (91/271/EEC), Water Reuse Regulation (2020/741), Nitrates Directive (91/676/

Fig. 10 Number of the examined articles per #No Sustainable Development Goal (SDG)



EEC). The energy sector embodies Renewable Energy Directive (RED II) (2018/2001/EU), Energy Efficiency Directive (EED) (2012/27/EU, revised 2018), European Green Deal, Just Transition Mechanism (JTM), Offshore Renewable Energy Strategy (2020), Hydrogen Strategy (2020). The food sector includes the EU goals as followed: Farm to Fork Strategy, CAP, EU Organic Action Plan (2021), EU Protein Plan (2018), Circular Economy Action Plan (CEAP) and environment sector encompasses EU Biodiversity Strategy 2030, European Climate Law (2021), Soil Strategy for 2030, LULUCF Regulation (Land Use, Land-Use Change, and Forestry), Zero Pollution Action Plan (2021). It is important to point out the study of Sydd (2025), in which the researcher assesses the implementation of the Farm to Fork strategy by farmers directly connected to food availability, opening new pathways for further research.

The last criterion of the current category is the “Relation to other goals”. Indicatively, the most cited goals are the Paris Agreement, the Intergovernmental Panel on Climate Change (IPCC), and the United Nations Environment Programme (UNEP), which are all essential components of international climate management and sustainability initiatives. Throughout the assessment of the articles, it was concluded that these guidelines contribute to the efficient confrontation of climate change by incorporating scientific knowledge, policy plans and integrated international action.

The alignment of agricultural research with these global benchmarks and international policy frameworks highlights a shift toward more integrated, systemic evaluations of sustainability. To effectively quantify the progress toward such ambitious targets as the SDGs or the European Green Deal, researchers require sophisticated analytical tools capable of

capturing the complex, economy-wide trade-offs between environmental protection and economic growth. Consequently, the following section examines the methodological landscape of CGE models, detailing the specific frameworks, production functions, and data structures utilized in the literature to simulate these global interactions.

3.6 CGE models

3.6.1 Types of CGE models

Multifold types of CGE models have been detected in the reviewed articles, and most of them belong to the Global Trade Analysis Project (GTAP) category of CGE modeling. A small proportion of other CGE models were also utilized in a few articles, including the Intertemporal Computable Equilibrium System (ICES) model, the Integrated Economic-Environmental Modelling (IEEM) model, the extended version of the Global Trade and Environment Model (GTEM), the GTEM-C model, the General Equilibrium Model of International-National Interactions between Economy, Energy and the Environment (GEMINI-E3) model, and the Global Responses to Anthropogenic Change in the Environment (GRACE) model (Fig. 11). Below is described the significant applications of the previously mentioned models. As illustrated in Fig. 11, ICES was implemented in four articles; IEEM, GTEM, and GEMINI-E3 in two articles; and the GRACE model was utilized only in one reviewed article. The main objective of the ICES model is the assessment of the climate change-induced welfare impacts on an economic scale, as well as the evaluation of mitigation and adaptation policies and the trade and public policy modifications in accordance with the conventional CGE (Bosello et al. 2018 a; *ICES – Intertemporal Computable Equilibrium System*, n.d.). The IEEM model is particularly useful for the portrayal of the interconnection between the economy and the environment, generating indicators that provide the capacity for decision-makers to evaluate in a quantitative way strategies to accomplish complex policy goals, such as SDGs, green growth targets and decarbonization plans (Banerjee 2019; Banerjee et al. 2024). GEMINI-E3 provides a worldwide analysis of climate change and energy policies and evaluates GHGs emissions, considering economic indicators and household consumption (Ciscar et al. 2012; Bernard et al., 2008). The GTEM-C model integrates a fundamental macroeconomic general equilibrium framework with a bottom-up module for energy generation, encompassing the technical parameters of diverse energy innovations (Abeysekara et al. 2023; *Integrated Environmental Economic Modelling | GTEM-C*, 2024), while the GRACE model evaluates the long-term impacts of climate change-induced effects and the reduction measures of GHGs

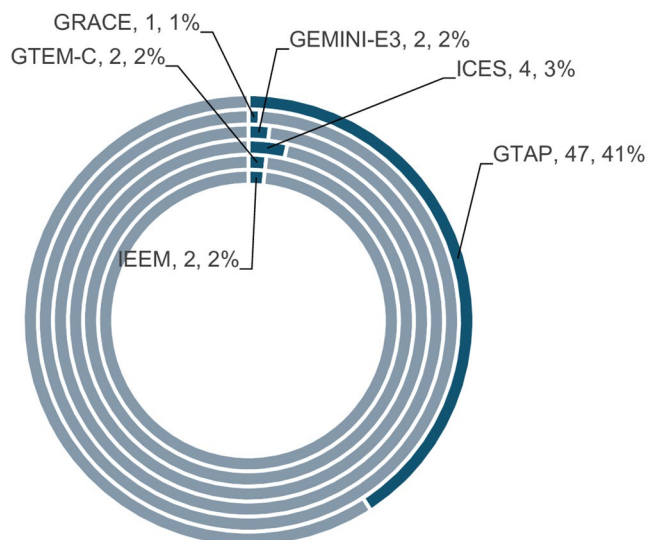
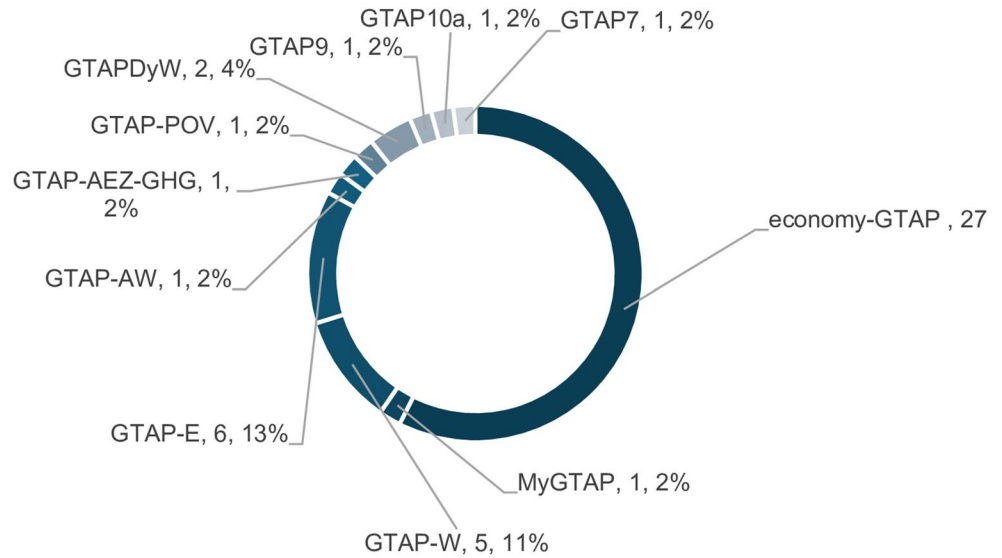


Fig. 11 Number of the reviewed articles that include the different types of CGE models, including GTAP models, ICES models, GEMINI-E3 models, GTEM models, IEEM models, and GRACE model

Fig. 12 The 47 different types of GTAP models that were detected in the reviewed articles



(Wei et al. 2017). Regarding the type of GTAP models that were mostly detected in the reviewed articles, these are the MyGTAP model, the GTAP-Water (GTPA-W) model, the GTAP-Energy-Environment (GTAP-E) model, GTAP-BIO-FCS, GTAP-AEZ, GTAP-AEZ-GHG, GTAP-DynW, GTAP9, GTAP10a, GTAP-AGR, GTAP-AW, GTAP-7, and GTAP-POV (Fig. 12). Generally, GTAP models are multiregional, multisector CGE models, providing integration and accuracy in the study research (Chalise And Naranpanawa 2016). The assessment of the reviewed articles revealed that the most widely implemented GTAP models were the GTAP-E model and the GTAP-W model, both of which are extensions of the original GTAP model. The GTAP-E model, as mentioned in the literature, measures the economic impacts of both climate change and the policy measures and strategies implemented to address it (Abeysekara et al. 2024). On the other hand, the GTAP-W model assesses the impacts of increasing irrigation efficacy, as well as climate change impacts on an international economy (Kahsay et al. 2017). The contributory role of implementing CGE models in the agricultural sector is emphasized for enhancing climate change mitigation measures and accurately predicting the long-term effects on agricultural productivity, social welfare, and the economy, particularly regarding GTAP models.

It is important to underscore that multi-region models (e.g., GTAP) are predominantly used (76%) because they are uniquely capable of capturing international trade linkages and global supply chain interactions, which are essential for regions heavily integrated into global markets (McDougall et al., 2007).

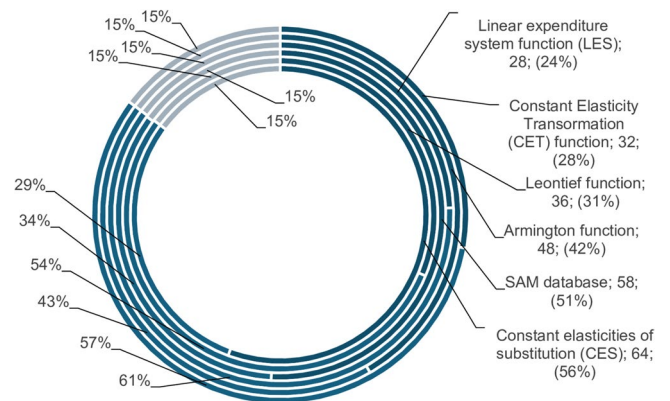


Fig. 13 Number of the reviewed articles that include CES function, Leontief function, SAM database, LES function, Armington function and CET function

3.6.2 Production function

The selection of the production function in CGE models is essential for depicting the relationship between inputs and outputs in the agriculture sector. The literature adopts various of functional forms to reflect a multitude of substitution elasticities, technological presumptions, and market relations. The primary production functions employed in the reviewed articles are as follows: Constant Elasticity of Substitution (CES), Leontief function, Social Accounting Matrix (SAM), Linear Expenditure System (LES), Armington function, and Constant Elasticity of Transformation (CET) function. A specific goal is performed by each function in the CGE modelling process, which affects the evaluation of the implications of climate change and sustainability on agriculture. As illustrated in Fig. 13 and 56% of the reviewed articles use the CES function, 51% use the SAM database, 31% of the reviewed articles use the Leontief function, 42% use the Armington function, 28% use the

CET function, and 24% of the reviewed articles use the LES function. In addition, the articles that don't use the CES function, the SAM database, the Leontief function, the Armington function, the CET function, and the LES function are 29%, 34%, 54%, 43%, 57%, and 61%, respectively. The reviewed articles that do not use any of the functions are labeled as "Non-available" (N/A). The percentage of them is 15% for every production function, as shown in Fig. 13.

The CES function is commonly applied in CGE models to determine the substitution of various production inputs, including labor, capital, land, and intermediate products. It allows for a constant elasticity of substitution across inputs, making it more flexible than fixed-coefficient production functions. To assess the way in which the agricultural sector adjusts to technological innovations, input price fluctuations, and policy changes, climate and sustainability-related CGE models largely employ CES functions (Zhu et al. 2021).

The Leontief production function is based on the assumption of fixed input proportions, which means that inputs are combined in fixed ratios with no potential for substitution. This function is especially pertinent for agricultural models that presume inflexible input structures, such as those that impose limitations on land, water, or labor. Despite the fact that Leontief functions are computationally simplified and data-efficient, they may restrict the capacity to record changes in technology and adaptive behavior in response to climate change (de Mesnard 2024).

SAM is a data-driven approach that depicts economic interactions throughout an economy, offering an extensive input-output framework that is frequently incorporated into CGE models. Although SAM is not a production function, it establishes the fundamental economic framework and the connections among sectors, which are essential for the calibration of the CGE-model. The analysis of sustainability initiatives is particularly pertinent to SAM-based CGE models, as they offer an extensive viewpoint on the

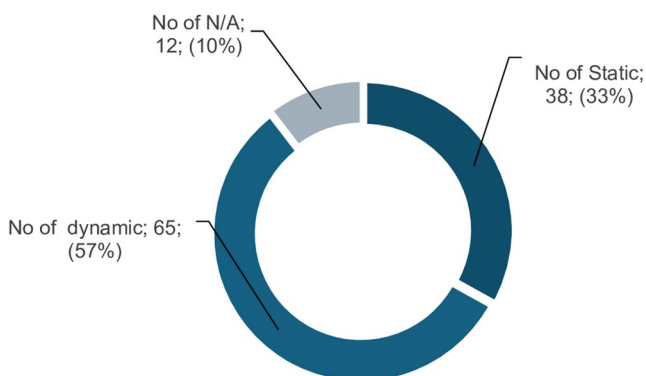


Fig. 14 Number of the reviewed articles that include static models or dynamic models. If the model is not classified in the article, it is marked as N/A

interactions between agricultural systems, labor markets, trade, and environmental factors (Ajatasatru et al. 2024; Ferrari et al. 2022).

The LES function is employed to simulate household consumption patterns in CGE models, with a particular emphasis on the analysis of food safety and agricultural demand variations in the context of climate change forecasts. The LES function is particularly useful in emerging markets where climate change impacts food availability, as it reflects income-dependent food demand trends, thereby increasing the veracity of agricultural CGE models (Laborde et al. 2021).

The Armington function is necessary for trade modelling in CGE models, particularly for the differentiation between agricultural products that are domestically produced and those that are imported. It is proposed that domestic and foreign products are inadequate substitutes, thereby introducing an elasticity of substitution between them. The Armington function is commonly employed in CGE models that focus on sustainability issues to assess the effects of climate change on international agricultural markets, trade practices, and carbon border modifications (Uuld And Magda 2022).

The CET function is equivalent to the CES function; however, it is employed to yield distribution instead of input substitution. It simulates the conversion of a single production process into multiple outputs, such as the allocation of land among various cultivations or livestock by farmers. CET functions are often implemented in property-use modelling throughout CGE models to evaluate the impact of climate policies on the distribution and sustainability of agricultural land (Mulanda And Punt 2021).

Scientific research employs a wide range of production functions to conduct studies on economic, agricultural, and other outcomes. The CES function and SAM database are mostly used in the examined articles regarding subjects such as climate change and agricultural and economic sectors.

3.6.3 Classification of CGE models

The literature on CGE modelling can be classified based on two fundamental dimensions: (i) the temporal structure of the model, distinguishing between static and dynamic approaches, and (ii) the spatial coverage, differentiating between single-region and multi-region models. Figure 14 depicts the number of the reviewed articles in which the application of their models was static or dynamic. It has to be clarified that in a small number of reviewed articles (10%) there were no data about the determination of the implemented model, i.e. on whether it was static or dynamic and these articles were defined as "Non-Available" (N/A). It has been estimated that 38 of the examined articles contained

static models, 65 articles included dynamic models, and 12 articles didn't contain either static or dynamic models.

Static models are used to compare a baseline equilibrium with a counterfactual scenario in the event of a policy change or disruption, typically at a single point (Wei et al. 2017). The instant or short-term effects of external disruptions, such as climate policies, subsidy changes, or trade liberalization on agricultural markets, are evaluated by these models, which do not completely consider economic growth in the long run. Static CGE models are frequently employed because of their minimal computational requirements and their capacity to conduct transparent comparative static analyses. Nevertheless, they fail to account for expenditure dynamics, capital accumulation, or intermediate economic modifications, which are essential for future policy evaluations (Arto et al. 2020).

Conversely, dynamic CGE models encompass time as a distinct dimension, which enables the collection of elements such as capital and labor, as well as intertemporal modifications. Such models can be either fully dynamic (intertemporal) or recursive-dynamic. Recursive-dynamic models progressively address equilibrium at every single time, with the present condition affecting the next period through capital stock updates, population expansion, and technological advancement. Intertemporal dynamic models, often framed as optimization problems, aim to maximize utility or profit over time by considering the evolving behavior of entities. Dynamic CGE models are especially beneficial for the analysis of the long-term effects of climate change policies, adaptation strategies, and the sustainability of agricultural systems (Moore et al. 2017).

According to Bhattarai, K. (2017), these dynamic models (detected in 65 articles) are more appropriate for regions focused on long-term sustainability and the SDGs, as they capture capital accumulation and technological advancements over time, whereas static models (38 articles) are

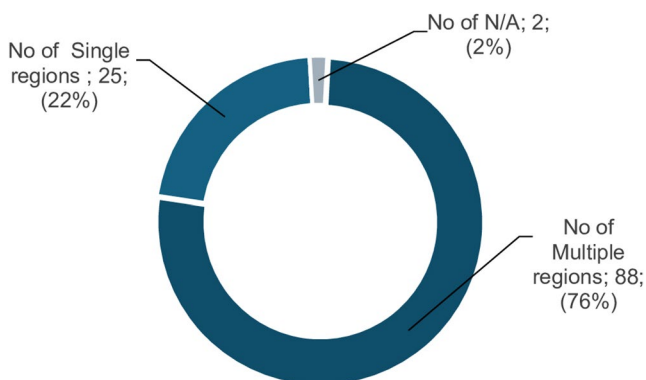


Fig. 15 Number of the reviewed articles in which the implemented models refer to a single region or multiple regions. If the region is not mentioned in the article, it is marked as N/A

better suited for immediate policy shocks or trade liberalization impacts.

The second classification criterion distinguishes CGE models based on their spatial scope, which may be categorized as either single-region or multi-region frameworks. Figure 15 demonstrated that 76% of the reviewed articles were conducted in multiple regions, while 22% were conducted in a single region. In two of the reviewed articles, the region was not mentioned.

Single-region CGE models emphasize a particular country or subnational area, evaluating the regional consequences of agricultural policies, environmental regulations, or climate change scenarios. Single-region models are especially applicable for policy evaluations that prioritize localized economic systems, limitations on resources, and policy interventions. Nevertheless, they may fail to consider the importance of international trade connections and global collateral effects in an international agricultural industry that is becoming increasingly interconnected (Zhang et al. 2022).

Multi-region models, also referred to as global CGE models, expand the analysis to encompass several countries or economic areas, thereby capturing worldwide policy interactions, supply chain relationships, and trade linkages. These models are crucial for the examination of worldwide sustainability and climate change policies, including transboundary resource management, agricultural trade liberalization, and carbon border adjustments (Manuel et al. 2021). GTAP (Global Trade Analysis Project) and IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) are two widely known multi-region CGE models that offer extensive international evaluations of policy scenarios. Although multi-region models provide useful information on global market dynamics, they necessitate a significant amount of data and computational capacity, which presents difficulties in their calibration and interpretation (Calzadilla et al. 2013).

In summary, the classification of CGE models is further categorized as dynamic or static models, as well as multiple-region or single-region models. After reviewing the available articles, it was found that dynamic and multi-region models are mostly used for scientific research due to their multiple advantages that have been analyzed above.

3.6.4 Data source

Regarding the data sources employed in the reviewed articles, this study mentions the most representative and extensively used data sources. The SAM database for the year 2007, the SAM database for the year 2011, the SAM database for the year 2015, the SAM database for the year 2019, GTAP database version 6, GTAP database version

7, GTAP database version 8, GTAP database version 9, GTAP database version 10, GTAP database version 11, the GTAP-E model, the GTAP-Water database, and Shared Socioeconomic Pathways (SSPs) are some widely utilized data sources that serve the needs of the conduction of the examined articles. Indicatively, version 9 of the GTAP database provides a worldwide financial situation for the year 2011 (Wilts et al. 2021), and GTAP 6 database depicts the global economy for the year 2001. Koopman et al. (2017) and Standardi et al. (2023) used the GTAP 8 for the year 2007, which is associated with the GTAP model specific to a nation. Moreover, the GTAP-E model which has been used in the study of Bosello et al. (2018) is based on GTAP 7 database and provides an overview of the global economic trends. SSPs are constructed for the evaluations of the climate change effects, adaptation strategies, and mitigation measures and are employed for demographic and GDP data (Hasegawa et al. 2015). Lastly, according to Ngoma et al. (2021) the usage of SAM databases in researches of climate change enables an accurate evaluation of the immediate and long-term consequences of climate change on the economy. More information about the detailed data sources that were used for the purposes of the reviewed articles are provided in the Supplementary Table 6 of Appendix A.

The diverse array of CGE models, production functions, and data structures previously detailed underscores the advanced analytical capacity required to simulate the economic and environmental complexities of modern agricultural systems. These modeling frameworks do not merely serve as descriptive tools but act as essential decision-support mechanisms for evaluating the effectiveness of specific interventions. Having established the methodological foundations used to quantify sectoral interdependencies and climate-induced shocks, it is necessary to examine how these simulations are applied to assess practical strategies for resource preservation. Consequently, the following section analyzes the primary **climate change mitigation measures**

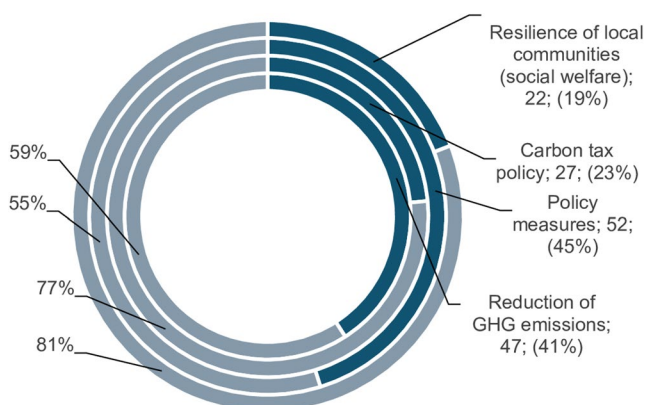


Fig. 16 Number of the reviewed articles including climate change mitigation measures

identified in the literature, ranging from the reduction of greenhouse gas emissions and carbon taxation to the enhancement of local community resilience.

3.7 Climate change mitigation measures

Given the detrimental impacts of climate change, previously examined and evident across various sectors, including the economic, environmental, social, and food production sectors, the implementation of mitigation measures is crucial to alleviate these repercussions. Throughout the detailed assessment of the reviewed articles, the existence of such mitigation measures and strategies regarding climate change effects, also functioning as criteria for the needs of the present study, has been pointed out. These are (i) reduction of GHG emissions, (ii) carbon tax policy measures, (iii) policy measures and (iv) resilience of local communities (social welfare) (Supplementary Table 4). As illustrated in Fig. 16, the larger amount of the examined articles includes policy measures for the decrease of the negative effects of climate change, with a percentage of 45%, followed by the measures referring to the reduction of GHG emissions (41%). Afterwards, the carbon tax policy and the resilience of local communities are more rarely applied in the reviewed articles as measures to mitigate climate change, with rates of 23% and 19%, respectively. These findings indicate the fundamental role of implementing policy measures and measures for the reduction of GHG emissions, since they are more applied for the confrontation of the climate change-induced effects.

Regarding the GHG emissions, Guo et al. (2020) state that agricultural activities are the primary contributors to carbon emissions on an international scale. Particularly, in the study of Xiao et al. (2024), it is found that chemical fertilizers are the main driver of the ecosystem's footprint, reaching almost 22.9%. This finding leads to the commitment of all nations to implement efficient measures for the reduction of carbon emissions, as well as all harmful GHGs that derive from other sectors besides agriculture. China has pledged to decrease its carbon emissions in terms of GDP by 60–65% from the point of 2005 to 2030 to accomplish its NDCs (Guo et al. 2020). In another relevant study conducted by Hasegawa et al. (2016a), the researchers examine the main mitigation strategies for the purpose of attaining Indonesia's mid-term carbon emission reduction goal. In general, the implementation of a carbon taxation policy system throughout the entire economy for the mitigation of the compliance costs is proposed (Gurgel et al. 2019). The study of Yang et al. (2024) presents that the implementation of multiple carbon-neutral measures and strategies at the same time provides more efficiency in reducing carbon emissions than a single policy. These include the feed-in tariff subsidy policy, clean energy sources, the carbon taxation

system, and carbon capture, utilization, and sequestration technologies. It is noteworthy to emphasize the CO₂ bio-conversion examined by Jeong et al. (2025), which contributes to carbon-neutral societies and enhances future society resilience. Long-term reduction of GHG emissions necessitates diverse policy modifications and the adoption of measures aimed at achieving the zero-emission target. Mitigation efforts should also be implemented, including sustainable land management, land use change, and forestry for the reduction of all pollutants. As agriculture is the main contributor to CO₂ emissions, some effective measures, including improvement in the efficacy of agricultural input usage, optimization of manure management and treatment, and promotion of sustainable cultivation techniques, need to be implemented (Zhang et al. 2022).

In addition, enhancing local communities' awareness and resilience regarding climate change strategies is a vital element in sustainable agricultural economies under climate change. The assessment of the reviewed articles has elucidated multifaced approaches, addressing both social welfare and local awareness. The promotion of awareness within local communities significantly influences the adoption of sustainable agricultural methods, resource preservation, and climate resilience practices. Training sessions for farmers on how to implement carbon-neutral agricultural methods, such as precision irrigation systems, biological cultivations and conservation tillage, as well as public initiatives and subsidies to enhance sustainable agricultural practices and methods, are some measures for public awareness. Correspondingly, it is important to ensure the resilience of local communities against climate-induced impacts (Pattanayak et al. 2009). In the reviewed articles, the term "social welfare" depends on variables such as employment, rural and urban consumption, household welfare, and income distribution. For instance, Hussein et al. (2013) highlight that one solution to improve social welfare is by introducing different income sources, such as clean energy generation, that do

not rely on agricultural activities, which are vulnerable to climate change impacts. Implementation of climate change mitigation strategies, such as reduction of GHG emissions, carbon taxation, policy measures and resilience of local communities, as well as the transition to renewable energy sources, leads to various beneficial effects regarding the confrontation of climate change-induced side effects.

The implementation of diverse mitigation strategies represents a critical initiative in addressing the multifaceted threats posed by a changing climate. However, the true efficacy of these measures cannot be fully understood without a rigorous quantitative assessment of their consequences across the entire socioeconomic and environmental landscape. By utilizing the comprehensive, economy-wide framework of CGE models, researchers can simulate the complex feedback loops triggered by these interventions. This leads to the next stage of analysis, which evaluates the specific sustainability impacts of model implementation, detailing how these computational frameworks measure outcomes in the economic, environmental, and social spheres.

3.8 Sustainability impacts of model implementation

The employment of CGE models in the agriculture field offers a thorough framework for the assessment of the sustainability impacts of a multitude of strategies and scenarios in light of climate change. Due to their multi-sectoral and economy-wide characteristics, CGE models provide the evaluation of sustainability from a comprehensive viewpoint, encompassing economic, environmental, and social aspects. This category outlines the sustainability impacts of the CGE model implementation by categorizing them as (i) environmental, (ii) economic and (iii) social impacts. Figure 17 demonstrates that the adoption of each model has vast impacts on the economic field (97%), as the economy is the most susceptible sector to fluctuations. Subsequently, the environmental impacts have an important proportion (54%) as a result of the models' implementation, followed by the social impact (43%).

3.8.1 Environmental

Agricultural activities have considerable environmental repercussions, especially in terms of water consumption, land deterioration, GHG emissions, and biodiversity degradation. CGE models are important for assessing the impacts of policy intervention on these environmental factors, offering valuable information towards the possibilities for sustainable resource management. In this subcategory the environmental impacts of the implementation of CGE

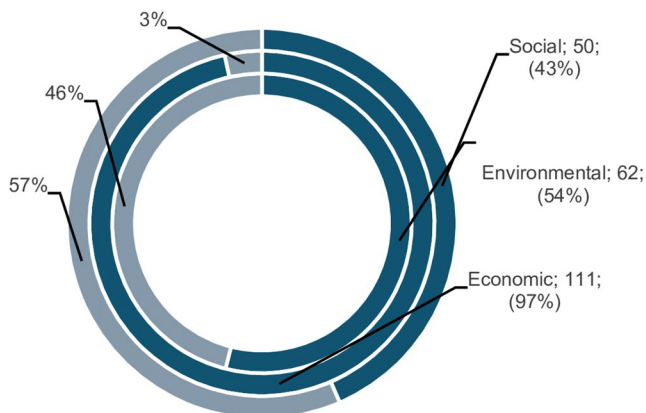


Fig. 17 Number of the reviewed articles, which include the impacts of the model implementation (environmental, economic, and social)

models are analyzed. CGE models evaluate the influence of reforestation programs, mitigation approaches, and carbon taxation on agricultural emissions. These models measure the impacts of emission mitigation strategies on agricultural output via the implementation of carbon tax policies and cap-and-trade procedures. Furthermore, the contribution of agroforestry actions, sustainable agriculture, and soil carbon storage in reducing climate change's adverse effects can be evaluated by CGE frameworks (Wang et al. 2024; Wills et al. 2023). CGE models present perspectives on effective land management strategies by the simulation of the economic consequences of deforestation, land deterioration and ecosystem preservation. The knowledge of trade-offs across biodiversity preservation and agricultural growth is further improved by the incorporation of environmental service estimation within CGE frameworks (Ferreira Filho And Horridge 2014). In addition, Timilsina and Mevel (2013) highlight the contributory role of CGE models on land-use change impacts as a result of the extension of biofuels to mitigate climate-induced effects. It is evident that the environmental impact of the CGE model implementation is widely estimated so as to reduce ecological footprint.

3.8.2 Economic

Regarding the economic field in which the effects of the implementation of bioeconomic models are most evident, many comprehensive studies have been conducted to assess the sustainability of economic impacts, including macroeconomic indicators, GDP, income distribution, investments, etc. This subcategory assesses the economic sustainability effects of the CGE model's implementation, with a special focus on agricultural productivity and output prices. More precisely, Chalise et al. (2017) evaluate the macro- and microeconomic impacts after the implementation of a static multi-household CGE model on Nepalese agriculture. Their findings indicate that the commodity prices will rise, resulting in difficulties among rural households, if immediate adaptation strategies aren't applied. Another study assesses the economy-wide effects after the employment of a CGE model in Turkey, providing a comprehensive approach. The findings of the study point out that the economic sector is strongly dependent on the agricultural and food production sectors and, particularly, on fluctuations in food production price. The abovementioned findings indicate the intricate interactions between the agricultural sector and the economy as a whole, as CGE models provide useful perspectives on the ongoing economic sustainability of policy initiatives. Arndt et al. (2015) employ a static economy-wide model to estimate the economic development of Ghana under the prism of climate change and observe that Ghana's economy will be severely affected without the implementation of

resilient adaptation measures. Lastly, CGE model implementation has major effects on the economic sector, and various studies have elaborated on the economic impacts and their close interconnection with agriculture.

3.8.3 Social

Social impacts of the CGE models' implementation concern the global academic field at a lower rate in comparison with the economic and environmental impacts. However, assessing the social sustainability impacts of CGE models applied in agriculture has been deemed important for improving the accuracy of anticipated results. Ngoma et al. (2021) underline the strong interrelationship between climate change-induced impacts and social welfare and how CGE models can estimate the rate at which welfare can be reduced in terms of climate change variability. Furthermore, the assessment of social resilience through various climate change policies, such as tax revenues, is illustrated in the study conducted by Diallo & Wouterse (2023). In a relevant study, it is found that the carbon pricing had a positive effect on social welfare, as well as the entire economy (Berthe et al. 2023). Wang et al. (2021) state that CGE models elucidate the impact of climate change fluctuations and policy changes on food prices and food availability, thus influencing the population's accessibility to food supply. The social impacts that emerged after the implementation of CGE models are gaining concern recently, and many studies focus on the way these models affect social welfare.

While the individual assessment of economic, environmental, and social impacts provides a clear categorization of CGE model outcomes, a descriptive overview alone is insufficient for a truly multidimensional evaluation. To capture the full complexity of these systems, the analysis must move from identifying separate effects to uncovering the statistical interdependencies between resource pillars and sustainability results. Consequently, the following section employs a rigorous cross-analysis to explore the specific correlations between the WEF Nexus dimensions and the identified impact categories, revealing how these interconnected elements drive systemic resilience.

3.9 Correlation between WEF Nexus framework and Sustainability impacts of model implementation

To transition from a descriptive categorization to holistic evaluation, a statistical cross-analysis was conducted to investigate the association between the 4 WEF Nexus dimensions and the sustainability impact categories (environmental, economic, and social). Fisher's Exact Test was employed to determine if the presence of a specific Nexus

node in a study is significantly associated with the evaluation of a specific sustainability impact (Vierra et al. 2023). The summary results of this analysis (Table 1) and the corresponding significance heatmap (Fig. 18) reveal several critical intersectoral dependencies.

As illustrated in Table 1, a highly significant association ($p < 0.001$) was identified between environmental protection and environmental impacts, suggesting that CGE models internalizing ecosystem pillars are predominantly utilized to evaluate biophysical outcomes. Similarly, energy generation demonstrates a strong significant correlation with environmental impacts ($p = 0.002$), highlighting the thematic alignment of energy-focused research with broader environmental sustainability goals. Notably, food security acts as a multidimensional bridge, showing statistically significant links to both environmental ($p = 0.013$) and social impacts ($p = 0.037$), which reflects its dual role in connecting natural resource availability with human welfare indicators, including poverty reduction and household resilience. Conversely, water management does not show a statistically significant association with any single impact category ($p > 0.05$), indicating its role as a cross-cutting driver that influences diverse economic and social variables without being uniquely tied to one specific sustainability pillar in the examined literature (Di Leo And Sardanelli 2020).

Consequently, the statistical cross-analysis highlights the foundational role of the environmental impacts of model implementation across the WEFE dimensions, demonstrating a highly significant association between environmental protection and environmental impacts ($p = 0.000$). In addition, food security is directly associated with environmental and social impacts of model implementation and represents the only WEFE dimension with a significant correlation to social impacts ($p = 0.037$); thus, social impacts of model implementation are exclusively dependent on the food security index (Fig. 18).

4 Discussion

The implementation of CGE models in agricultural sustainability and climate change mitigation areas has revealed significant insights into the interlinked nature of economic, environmental, and social factors. This section synthesizes the results, identifies concrete research gaps, explores opportunities, trends, and theoretical and practical implications, considers the policy implications of this study for sustainable food systems, and provides future research pathways of CGE implementation in agriculture.

Table 1 Association between WEFE Nexus dimensions and Sustainability Impact Categories using Fisher’s Exact Test

WEFE nexus dimension	Sustainability impact category	Fisher’s exact (p-value)	Sig-nificant ($\alpha = 0.05$)
Water Management	Environmental	0.576	-
Water Management	Economic	0.635	-
Water Management	Social	0.571	-
Energy Generation	Environmental	0.002	**
Energy Generation	Economic	1.000	-
Energy Generation	Social	0.849	-
Food Security	Environmental	0.013	*
Food Security	Economic	0.324	-
Food Security	Social	0.037	*
Environmental Protection	Environmental	0.000	***
Environmental Protection	Economic	0.125	-
Environmental Protection	Social	1.000	-

Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. “-” indicates no significant association

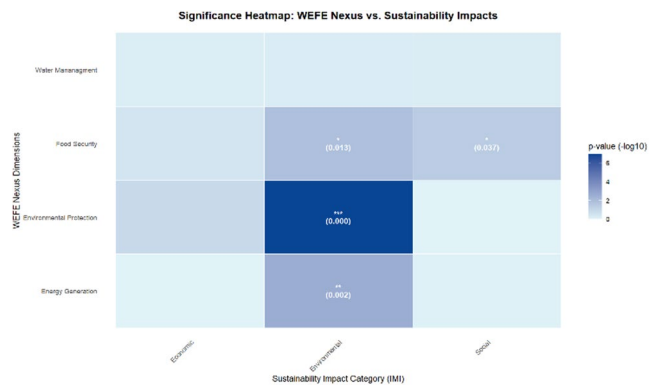


Fig. 18 Significance Heatmap: WEFE Nexus vs. Sustainability Impacts

4.1 Critical reflection on the state of CGE modeling in agriculture

The examined literature highlights the complex interaction between agricultural productivity and climate change. The severe impacts of climate change on agricultural production, involving unpredictable weather conditions (Wei et al. 2017), shifts in precipitation patterns (Siddig et al. 2020), and temperature fluctuation (Arndt et al. 2014), have led to increased food insecurity (Zidouemba And Gerard 2018), economic instability (Khan et al. 2020), and environmental deterioration (Banerjee et al., 2022). For instance, it is stated that the increasing rate of rising temperatures and the fluctuation in precipitation will have negative effects on crops, thereby reducing the agricultural productivity and leading to higher agricultural product prices. This will result in both worldwide and regional food price insecurity (Salvo 2013). Extensive global research has measured the significant

losses in agricultural productivity and crop yields due to climate change. These consequences have profound implications, as agricultural productivity serves as a primary driver of food availability and the stability of food prices. The CGE models synthesized in this review demonstrate that climate change exerts a profound influence on agricultural productivity (Khan et al. 2020), with subsequent repercussions for food prices (Banerjee et al., 2022), trade negotiations (Lee and Zhang 2009), and sectoral resource allocation (Sands et al. 2014). A significant body of research emphasizes that sustainable agricultural practices, such as precision irrigation (Kahsay et al. 2017), crop rotation (DUDU et al., 2010), and conservation agriculture (Chalise And Naranpanawa 2016), can alleviate these adverse effects while simultaneously enhancing resilience against climate-driven disruption. Furthermore, the integration of CGE models serves as a beneficial decision-support tool, enabling policymakers to conduct a comprehensive scenario analysis across a diverse range of economic and environmental conditions (Yalew et al. 2018). These CGE models facilitate the assessment of complex trade-offs between economic growth and environmental conservation, thereby guiding the development of policies designed to optimize both objectives. By incorporating both spatial and temporal dimensions, CGE models effectively account for regional disparities in climate-induced impacts, allowing for the formulation of targeted interventions that confront specific local vulnerabilities (Wilts et al. 2021). Through the assessment of the reviewed articles, several representative cases of the implementation of CGE models to address region-specific challenges were highlighted, most notably the mitigation of water scarcity in Southern European countries, where drought challenges more often occur. Given that these nations are heavily dependent on agricultural productivity, the stability of water supplies and irrigation infrastructure is paramount. In this context, CGE models serve as a vital tool for evaluating the economic viability of alternative water management strategies, such as the adoption of drip irrigation systems and water recycling technologies, to improve efficiency while maintaining high output levels. This example indicates the importance of CGE models in quantifying the economic impact of diverse water management practices (Koopman et al. 2015). Aside from that, two main issues that can be addressed by using CGE models are crop yield volatility and income inequalities among rural household, particularly in Sub-Saharan areas. CGE models address these challenges by simulating the economy-wide repercussions of climate change across diverse regions (Calzadilla et al. 2013). This is particularly vital in regions where agricultural production is a major contributor to economic growth but is progressively threatened by water scarcity, land degradation, and extreme weather events (BOYD and IBARRARÁN 2009).

The capacity of CGE models to project the long-term effects of policy decisions guarantees that adaptation and mitigation measures are both efficient and economically viable, as well as socially equitable (Hasegawa, Fujimori, Masui, et al., 2016b).

A major outcome of this study is the identified necessity to combine agricultural practices with climate mitigation objectives. To this end, carbon taxation, subsidies for sustainable farming practices, and initiatives for renewable energy generation in agriculture have been emerged as efficient policy approaches. Numerous studies evaluating the implementation of CGE models indicate that carbon pricing mechanisms facilitate the reduction of GHG emissions while maintaining economic welfare (Wąs et al., 2021). For instance, Xiao et al. (2017) evaluate the impact of CGE establishment on energy use efficacy, considering the entire economic system and the consequences caused by CO₂ emissions. However, the efficacy of these policies relies on the particular variables of each area, such as the financial system, resource availability, and governance guidelines (Gong And Huo 2024). In addition, international agreements, including the Paris Agreement (*The Paris Agreement* UNFCCC, 2015) and the European Green Deal (*The European Green Deal-European Commission*, n.d.), contribute significantly to the adoption of sustainable agricultural policies. The alignment of CGE modeling with the SDGs further underlines their importance in determining policies that balance economic development, environmental sustainability, and social equity. Specifically, SDG #1 (No Poverty) and SDG #2 (Zero Hunger) are greatly impacted by agricultural strategies, which are shaped by CGE models. These strategies seek to pinpoint techniques that enhance agricultural productivity and crop yields, thereby guaranteeing food security and economic opportunities for marginal populations. Furthermore, SDG #13 (Climate Action) is boosted through the assessment of climate adaptation and mitigation strategies, including carbon pricing systems and sustainable land-use practices, which can decrease GHG emissions and conserve agricultural productivity and yields. SDG #6 (Clean Water and Sanitation) and SDG #15 (Life on Land) are also affected by their incorporation of CGE models into policy formulation, which evaluates the long-term agricultural sustainable pathways of irrigation techniques, soil conservation actions, and biodiversity conservation. CGE models contribute to the adoption of renewable energy in the agricultural sector, thereby enhancing SDG #7 (Affordable and Clean Energy). This goal is accomplished through the reduction of the dependence on fossil fuels, such as petroleum and coal, and the adoption of agricultural approaches that use bioenergy and energy-efficient methods.

4.2 Barriers, opportunities, and trends

Despite their multitude of implementations, CGE models confront many limitations that require being addressed in future research. The scarcity of CGE applications specifically focused on EU countries, despite the strong relevance of European Green Deal objectives, suggests a methodological preference in Western academia for hybrid or sector-specific tools. However, as this study demonstrates, the transition toward a WEF Nexus approach necessitates the multi-sectoral lens that only CGE models provide, suggesting that future research should more aggressively apply CGE frameworks to European domestic agricultural policy to ensure macroeconomic consistency with sustainability targets. Another important limitation is the lack of capturing micro-level farm decisions, behavioral responses, and real-time climate adaptation strategies (ZESHAN And SHAKEEL 2023). However, the barriers that have been identified present transformative opportunities via combining CGE models with Agent-Based Models (ABM) and machine learning techniques, which could improve their accuracy as well as their predictability. Recently, there has been a major trend of using ABMs in the agricultural sector to simulate agricultural systems and the effects of policies (Groeneveld et al. 2017; Kremmydas et al. 2018; Nolan et al. 2009). These models can serve as an innovative addition to traditional agricultural models in the context of policy analysis, and their implementation relies on artificial intelligence, machine learning techniques, and deep learning (Kremmydas et al. 2018; Rodríguez-Aguirre et al. 2025). Agent-based modelling is a procedure that relies on a “bottom-up” approach, designed to simulate unanticipated events by encompassing the behaviors of autonomous agents and the interactions through which agricultural systems are developing. This approach does not require the establishment of predetermined assumptions concerning the entire system characteristics (Helbing 2012; Kremmydas et al. 2018). Berger and Troost (2014) underline the importance of ABMs as an essential tool for evaluating the farmer’s perspective on climate change in agriculture and the impacts of policy (Berger And Troost 2014). This model has been beneficial for optimizing water management by examining water flow in the upper soil layer and irrigation methods (Lopez-Jimenez et al. 2024). Consequently, ABM is a useful tool for both enhancing the comprehension of farmers’ responses in view of environmental, economic, or social changes, especially at a regional scale, and for indicating optimized agricultural methods; therefore, coupled with dynamic bioeconomic models may result in significant outcomes for future agricultural management (An 2012; Magliocca et al., 2015). A determinant improvement of the CGE model’s application in the area of agriculture could

also be their combination with machine learning techniques (including their subset, deep learning), as well as Artificial Intelligence (AI). A large number of studies have been conducted to assess the effects of these innovations in agriculture. More precisely, machine learning techniques contribute to the promotion of intelligent irrigation systems, crop disease detection, soil monitoring, and water scarcity tracking in cultivation. Further, various AI systems can analyze the inputs and outputs of cultivations so as to provide integrated crop management by minimizing the input costs and maximizing the profits (Jagtap et al. 2022). Machine learning and deep learning systems are making their entry to Precision Agriculture (PA), thus promoting sustainable agricultural approaches, which use precision irrigation as they promote the maintenance of natural resources (Olabimpe Banke Akintuyi 2024). In addition, future research should focus on improving the representation of non-market ecosystem services, land-use changes, and water-energy interactions within CGE frameworks. Improved data availability and cross-sectoral modelling approaches will further reinforce the capacity of CGE models to promote sustainable agricultural transitions. Finally, the ongoing development and implementation of these models will be crucial in directing agriculture toward a sustainable, climate-resilient future, thereby assuring food availability and preserving natural resources for future generations.

4.3 Theoretical and practical implementation of CGE models

The theoretical contribution of this study lies in its shift from a descriptive synthesis to a holistic evaluation of the WEF Nexus within CGE frameworks. CGE models function as an effective tool for assessing climate policies and sustainability initiatives within agricultural fields (Mukashov et al. 2024). The literature points out the capacity of these models to accurately illustrate the intricate relationships among WEF resources (Raviv et al. 2024). By adopting a multi-sectoral lens, CGE models present a holistic framework for evaluating the wider socio-economic and environmental implications of agricultural policies (Hasan And Thurlow 2011). Nevertheless, certain constraints continue to exist, especially in the depiction of regional climate impacts, agricultural adaptation practices, and the deployment of technology in agriculture (Farajzadeh et al. 2024). The implementation of CGE models enhances resilience and adaptive capacity by embedding sustainability metrics directly into decision-making processes (Amiri et al. 2021). By predicting a variety of economic and environmental problems, these models empower policymakers to project the long-term effects of resource allocation policies, climate adaptation techniques, and technological

advancements (Hasegawa, Fujimori, Masui, et al., 2016b). This approach guarantees that agricultural developments are not only profitable but also in accordance with SDGs, thereby decreasing dependency on non-renewable resources and mitigating environmental deterioration. Additionally, CGE models have the advantage of establishing incentives, including subsidies for climate-smart technological innovations or carbon pricing mechanisms, that contribute to the adoption of sustainable practices by farmers (Roson And Sartori 2014). Through these economic approaches, it becomes possible to internalize the external costs of agricultural production, thereby ensuring that environmental and social costs are precisely reflected within market prices. Furthermore, the data acquired from CGE models serve to enhance worldwide trade balances by elucidating the potential economic and environmental consequences of trade guidelines, which in turn fosters international collaboration in addressing global long-term sustainability concerns (Britz & Hertel, 2011). For instance, the study of Bassi et al. (2025) introduces the CBAM, which prevents carbon leakage through the implementation of taxes on imports from nations that lack climate policy laws. In this case, the role of CGE models is to forecast the long-term economic consequences of the implementation of CBAM on countries that export and import goods by projecting modifications to trade balances, production costs, and carbon emissions.

In practice, CGE models serve as a framework for assessing the sustainability impacts of agricultural strategies and climate change scenarios. The implementation of CGE modeling in agriculture provides a robust decision-support tool that bridges the gap between macroeconomic policy and on-farm sustainability (Tanure et al. 2023). These models are implemented to evaluate a broad spectrum of environmental factors, including the influence of reforestation programs, carbon taxation on emissions, and effective land management strategies (Ji et al. 2022). Economically, CGE applications simulate economy-wide effects on GDP, income distribution, and commodity price fluctuations to guide the development of resilient adaptation measures (O’Ryan et al. 2023). Socially, these models are utilized to estimate impacts on social welfare, household resilience, and the population’s accessibility to food supplies under varying policy conditions (Zhang et al. 2022). By facilitating rigorous scenario analysis and the assessment of trade-offs between economic growth and environmental preservation, CGE frameworks act as vital decision-support tools for policymakers, enabling targeted interventions, such as precision irrigation or renewable energy subsidies, that align agricultural expansion with SDGs. Ultimately, they are employed to establish practical incentives, such as carbon pricing and subsidies for climate-smart innovations, which encourage farmers to adopt sustainable practices by

internalizing external environmental and social costs into market prices.

In essence, the multifaceted application of CGE models provides the necessary analytical depth to harmonize global trade and national policy with local agricultural realities, ensuring a resilient transition toward sustainable food systems.

4.4 Policy implications and stakeholder strategies for sustainable food systems

The findings of this study offer a strategic roadmap for governments and industry stakeholders to transition toward more resilient and sustainable food systems through the targeted application of CGE models. Based on the statistical findings of the cross-analysis between WEF Nexus dimensions and sustainability impacts, as well as the specific associations identified through the Fisher’s Exact Test (Di Leo And Sardanelli 2020), various stakeholders can better align their interventions with the multi-sectoral realities of agricultural systems.

Particularly, the highly significant correlation between environmental protection ($p < 0.001$) and energy generation ($p = 0.002$) with environmental impacts highlights that CGE models are exceptionally robust at simulating biophysical outcomes like GHG mitigation and carbon-neutral transitions. Governments should utilize CGE models to calibrate NDCs and design carbon taxation systems that accurately reflect ecological costs. On the other hand, the dual significance of food security for both environmental ($p = 0.013$) and social ($p = 0.037$) impacts provides a mandate for integrating social safety nets with agricultural policy. Governments can use these findings to ensure that climate adaptation measures, such as precision irrigation or crop rotation, simultaneously protect the incomes of marginal rural populations. Ultimately, the lack of a specific single-pillar association for water management ($p > 0.05$) suggests it serves as a foundational driver across the entire economy. This necessitates a policy approach where water security is treated as an essential short-term short-circuit risk for all other economic sectors.

For industry stakeholders the aforementioned findings translate into risk management and supply chain resilience. Industry stakeholders in energy-intensive agricultural sectors must align their investment strategies with the strong energy-environment link. Using CGE-based projections, industries can evaluate the long-term profitability of transitioning from fossil fuels to renewable sources like photovoltaics or bioenergy. In addition, the unique social-environmental bridge provided by food security indicates that corporate supply chains are highly vulnerable to social instability and malnutrition in production regions.

Stakeholders should utilize CGE insights to forecast food price fluctuations and implement adaptive management to ensure long-term availability. The findings regarding resource interdependencies are critical for industries navigating the CBAM. Industrial stakeholders can use these modeling frameworks to anticipate how trade levies on high-carbon imports will shift production costs and influence global market competition.

By integrating the WEF Nexus approach into CGE modeling approaches, governmental structures and industry stakeholders can transition from fragmented interventions toward a holistic governance framework better anticipate price fluctuations and resource scarcities, ultimately fostering a more stable and ecological food production environment.

4.5 Limitations of the study

Although this SRL provides a comprehensive synthesis of CGE applications in agricultural sustainability, certain limitations must be acknowledged. With a view to the database and language scope, this study was restricted to the Scopus and Web of Science databases, which, while extensive, may have excluded relevant grey literature, government reports, or studies published in languages other than English. In addition, by focusing exclusively on CGE frameworks to ensure economy-wide consistency, this review necessarily omitted insights from specialized bioeconomic tools, such as EPIC, IMAGE, or IMPACT models, that, despite lacking macroeconomic feedback loops, offer higher-resolution biophysical data for specific crop yields. Finally, the current concentration of CGE research in specific regions may lead to a geographic bias, leaving a critical need for more domestic CGE applications within the EU to align local policy with the European Green Deal.

4.6 Future research directions and recommendations

To advance the field, future research must prioritize the integration of AI and machine learning into CGE frameworks to enable real-time detection of crop diseases, soil monitoring, and precision irrigation needs. The implementation of ABM to evaluate the farmer's perspective on climate change will ensure that policy measures are both efficient and socially equitable. Furthermore, enhancing the representation of non-market ecosystem services within CGE frameworks is a critical future pathway for evaluating the true costs of agricultural impacts on biodiversity and land health. Such methodological improvements represents a vital step toward optimizing CGE model implementation and ensuring the sustainability of agricultural landscapes.

In line with future research priorities, the optimization of the upcoming development of the Dynamic Agricultural Household Bio-Economic Model (DAHBSIM) has received restricted research attention despite its potential to maximize rural household utility. The literature refers to DAHBSIM as being used to simulate scenarios associated with policies and economic initiatives to enhance household welfare in rural areas, where the consumption of agricultural products varies among each household. The main objective of the specific model is the maximization of the utility of the farm household (El Ansari et al. 2023). In the same study, the researchers employ the DAHBSIM model to assess the social, economic, food consumption, and environmental impacts of various motivations for sustainably increasing cereal, legume, and vegetable production. To confront issues related to biophysical limitations on agricultural productivity and yield, as well as the whole-farm effects of alternative approaches to sustainable agriculture intensification, the DAHBSIM model has been introduced. This particular model encompasses production and consumption in terms of each individual household (Flichman 2015). Future research should be directed at optimizing the model's input parameters, as well as improving the accuracy and effectiveness of its outputs. This will improve the efficacy of the DAHBSIM approach in relation to sustainability and climate change.

Concluding, the employment of dynamic bioeconomic models in the agricultural productivity sector is crucial, as they incorporate economic decision-making with biophysical procedures, offering both a comprehensive evaluation of the sustainable crop management and the climate change-induced implications. Contrary to static models, dynamic bioeconomic models include temporal changes within parameters such as water accessibility, technological developments and policy initiatives, enabling a more accurate simulation of long-run agricultural dynamics (Castro et al. 2018). These models have the potential to establish a connection between economic decisions and environmental boundaries, promoting sustainability in the agricultural sector under the prism of climate change.

5 Conclusions

In conclusion, the integration of bio-economic models in the agricultural sector, and more specifically the implementation of CGE models, has gained multidisciplinary interest in recent years. Driven by the rapid onset of climate change and its systemic global threats, there is an urgent need to address these challenges by implementing dedicated tools and methods, such as dynamic bioeconomic models in vulnerable agricultural systems. The incorporation of CGE

models in agricultural sustainability research provides beneficial insights into the complex correlations across economic development, social stability, climate mitigation, and resource preservation. Particularly, CGE models optimize resource allocation, improve productivity and yields, and mitigate climate change effects by providing a comprehensive framework for evaluating economic, environmental, and social interdependencies. Furthermore, they facilitate a precise and robust assessment of the long-term impacts of climate adaptation policies and technological innovations in agriculture, enabling policymakers, researchers, and stakeholders to identify cost-effective pathways for sustainable development. As previously examined, the assessment of these bioeconomic models facilitates sustainable agriculture and integrated input-output management, ensuring the preservation of natural resources. The outcomes of the present study underline the growing interest of CGE models as a tool for addressing current agricultural challenges, particularly in light of sustainability and climate change mitigation consciousness.

This study conducted a SLR on CGE implementation in agriculture, focusing on sustainability and climate change, established robust criteria for the comprehensive evaluation of CGE modeling in the agricultural sector and identified gaps requiring improved integrated approaches. Eight thematic topics were identified, and 30 criteria were employed to assess the article. Out of the 9,673 documents found, 255 full-text articles were assessed, and 115 were incorporated in this study. These articles were classified and evaluated across the topics of “Field information”, “WEFE Nexus approach classification”, “Impacts of climate change”, “Relation to international initiatives and goals”, “CGE models”, “Climate change mitigation measures”, and “Sustainability impacts of model implementation”. For each of the abovementioned topics, a number of criteria were developed to facilitate the assessment of the reviewed articles and result in valid integrated outcomes. The results of this study have been elaborated and evaluated on multifold levels, considering every possible factor that could affect and be affected by the implementation of CGE models. The study’s focus remains disproportionately concentrated on economic outcomes (97%) of CGE models’ implementation compared to environmental (54%) and social (43%) dimensions. A key insight of this study, mainly derived from the statistical cross-analysis of the WEFE Nexus, is that food security serves as the primary “bridge” between environmental and social sustainability impacts ($p < 0.05$), indicating its crucial role on both resource integrity and social stability. A highly significant association ($p < 0.001$) was identified between environmental protection and environmental sustainability impacts, suggesting that CGE models internalizing ecosystem pillars are predominantly utilized to evaluate

biophysical outcomes. Similarly, energy generation demonstrates a strong significant correlation with environmental impacts ($p = 0.002$), highlighting the general alignment of energy-focused research with broader environmental sustainability goals. On the other hand, water management acts as a foundational, cross-sectoral driver that affects economic, social, and environmental variables without being connected to one specific sustainability factor. These findings underline the vital contribution of the WEFE Nexus in sustainable agricultural systems and the need to include this integrated context in the CGE modelling implementation.

After assessment of the selected articles, it has been found that the economy is the most excessively affected sector by climate change-induced impacts (96%), followed by the environment (86%). This finding indicates that CGE models need to prioritize mitigation measures in specific sectors in order to effectively address the current challenges. A major field that has been elaborated on the present study and is gaining worldwide interest is the SDGs, with a specific focus on #1 No poverty, #2 Zero Hunger, and #13 Climate Action. Along with the incorporation of the SDGs in the current study, climate change mitigation measures and, more precisely, reduction of GHG emissions, carbon taxation, policy measures, and resilience of local communities (social welfare) are key criteria for the conduction of integrated outcomes of this study.

Although these models serve as a valuable empirical tool for policymakers, farmers, and scientists, it is necessary to address current constraints through continuous methodological developments and interdisciplinary methodologies. To offer a feasible way forward, this study highlights 3 areas for immediate progress in agri-food systems. First, governments should transition from generic modeling to policy-integrated CGE frameworks to calibrate NDCs and design carbon taxation systems that specifically protect rural household incomes. Second, industry stakeholders must operationalize CGE-based scenario analysis to mitigate supply chain vulnerabilities under international regulatory shifts. Third, to bridge the shortcoming of the micro-level farm decisions, behavioral responses, and real-time climate adaptation strategies identified in the methodology, the most promising technical pathway lies in the combination of CGE models with ABM and Machine Learning. Such integration, particularly through DAHBSIM model, will allow for the internalization of real-time farmer behaviors and precision-agriculture adoption rates. However, DAHBSIM studies are still at an early stage, and more research needs to be carried out to ensure efficacy and accurate results, which will serve as ultimate tools in the agricultural sector, considering climate change impacts. Furthermore, the development of climate-smart agricultural technologies, including precision agriculture and Decision Support Systems (DSS tools),

are some innovative measures for the increase of efficacy regarding agricultural productivity and the promotion of sustainability under the prism of climate change. The incorporation of AI systems in agriculture aims to reduce crop inputs and enhance crop yields by accurately detecting the needs of crops, thereby contributing to resource security and mitigating climate change-induced impacts resulting from the overuse of agricultural inputs.

Ultimately, the outcomes of this study demonstrate that achieving sustainable food policies requires moving beyond isolated economic optimizations toward integrated socio-ecological systems. Future research should prioritize the refinement of model input parameters and the inclusion of behavioral economics technologies, leveraging technologies such as ABM and AI, to ensure that agricultural strategies are not only economically profitable but also socially equitable and ecologically resilient. By adopting these integrated, climate-smart methodologies, the agricultural sector can move toward a holistic governance framework that effectively aligns productivity with global sustainability targets.

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Declarations

Competing interests The authors declare no competing interests.

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