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Getting (ECO)Ready: Does EU Legislation Integrate Up-to-Date Scientific Data for Food Security and Biodiversity Preservation Under Climate Change?

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Abstract: European policies on climate change (CC), food security (FS), and biodiversity (BD) represent the EU's commitment to a sustainable agri-food system, highlighting the interdependence between environmental health and food security. By analyzing key drivers and indicators, the present study evaluates the effectiveness of existing measures and identifies gaps in the policy framework. A Scoping Group activity facilitated dialogue between policymakers, industry, and farmer representatives to gather feedback and strengthen the data–policy link. The results highlight progress in areas such as promoting sustainable agriculture and biodiversity, while pointing out unresolved issues like the challenges faced by smallholder farmers. The study emphasizes the need for real-time monitoring tools and tailored solutions to address the complexities of the agri-food system. It also encourages the integration of emerging technologies, such as IoT and AI, to enhance the sustainability of agricultural practices. Ultimately, the findings call for a landscape-specific approach to maximize biodiversity gains, mitigate climate impacts, and ensure food security within the broader context of the EU's ecological and socio-economic challenges.

Keywords: agricultural resilience; biodiversity; climate change; food security; European Union policies; sustainable agriculture

1. Introduction

Over the last decade, the European Union (EU) has taken significant developments towards addressing the pressing challenges posed by climate change and biodiversity loss for ensuring food security. The Green Deal, its enclosed Farm to Fork strategy (F2F), and the Common Agricultural Policy are clear examples underscoring the EU's commitment to a sustainable and resilient future. These policies reflect a shared vision towards sustainable development, acknowledging the complex links between climate crisis, biodiversity, and food security. By prioritizing the reduction in greenhouse gas (GHG) emissions and promoting a circular economy, the Green Deal highlights the need for systemic change in agriculture and food production. The F2F Strategy aims at transforming the entire food supply chain. By encouraging reduced pesticide use, the limited use of antibiotics, and a shift towards organic/sustainable practices, this strategy highlights the interconnection between environmental health and our ability to ensure safe nutrition. Implicit in this approach is the need to understand how climate-induced alterations, as well as biodiversity loss, impact not only the production but also the quality and accessibility of food [1–4]. The current EU Common Agricultural Policy (CAP) includes some elements, in terms of rules and tools, towards a more sustainable and environmentally friendly agricultural sector, the so-called 'green architecture of the CAP'. For example, by incorporating 'eco-schemes' that reward farmers for adopting environmentally friendly practices, the CAP recognizes the crucial role of biodiversity in maintaining resilient ecosystems.

However, the criteria for eligibility have proven to be unsuitable for smallholder farms. European farmers engaged in eco-schemes face either additional costs or decreased incomes due to the reduction in production intensity, as well as competition from imported products from countries that do not follow strict EU guidelines. Nevertheless, they are eligible for financial compensation annually [5]. Climate change and biodiversity loss are intrinsically linked and together pose a significant threat to global food security. Extreme weather events, shifts in crop growing seasons, and the loss of pollinators are just a few examples of how climate oscillations may affect agriculture [6–8]. Understanding this nexus allows for the formulation of strategies that ensure food security in the face of a changing climate [9]. Constituted by four pillars (availability, access, utilization, and stability) food security is a multidimensional concept. It is closely connected with the Sustainable Development Goals (SDGs) and is considered a key element of them, particularly within Goal 2, which aims for zero hunger. The scientific literature has raised concerns about these interrelationships by suggesting the addition of further variables, particularly those associated with biodiversity and climate change [10]. Furthermore, the strict relationships between food security and sustainability require a comprehensive multidisciplinary assessment. Fundamental determinants are agricultural practices, alternative sources of food supply, and public fostering of more sustainable food security schemes [11,12].

During the complex policy decision-making process, the scientific community plays a significant role, particularly in the context of policy documents related to the recent environmental sustainability laws. The role of the scientific community becomes increasingly important, especially when addressing legislation related to complex issues like food security. In a world that is increasingly becoming more globalized, policymakers must recognize that food insecurity in one region could yield substantial political, economic, and environmental turbulence elsewhere. Consequently, despite the actions of various global organizations like the Food and Agriculture Organization of the United Nations (FAO) and the United Nations (UN), the challenge of food insecurity is escalating. This escalation underscores the necessity for more efficacious and sustainable solutions to ensure the mitigation of food insecurity and the sustainability of food production. Implementing landscape-specific and tailored climate-friendly agricultural production methods provides a dual solution to the challenges of food security and climate change. This involves intensifying agricultural production while minimizing environmental stresses to ensure the sustainable long-term production of food [13,14]. Although this sustainable intensification strategy is part of the policy agenda for numerous governments worldwide, it has faced criticism for its perceived emphasis on production or a lack of coherence. In the twenty-first century, the primary mission is to establish a sustainable food system, challenging a more concrete policy framework than the currently existing one. Unfortunately, this mission has been impeded by competing solutions for policy focus and policies that have, so far, failed to integrate evidence from social, environmental, and economic components into a comprehensive and cohesive policy response. Climate change is forcing millions of people into a cycle of food insecurity and poverty. Nonetheless, addressing both food insecurity and climate change requires the urgent adoption of climate-friendly agricultural production methods [15,16].

The present work, part of the EU Eco-Ready project (https://www.eco-ready.eu, accessed on 31 January 2024, European Union's HORIZON-CL6-2022 Research and Innovation Programme, Grant Agreement No. 101084201), systematically identifies and examines key European policy documents on climate change (CC), food security (FS), and biodiversity (BD) to detect gaps and connections with scientific literature, providing tools for a sustainable transition resilient to climate change and biodiversity loss. Specifically, this study is guided by the following research questions:

1. Are current European policies effectively addressing the interconnected challenges of climate change (CC), food security (FS), and biodiversity (BD), or are there gaps in their integration and implementation?
2. To what extent are scientific data on CC and BD integrated into policymaking, and how can scientific research contribute to improving the effectiveness of existing measures?
3. Can engagement with diverse stakeholders provide actionable insights to bridge data–policy gaps and enhance policy relevance?

To explore these questions, a comprehensive list of drivers and indicators was compiled and analyzed, serving as essential tools for assessing the effectiveness of existing measures. Furthermore, a Scoping Group activity was set up to foster dialogue with key policy actors (EU DG representatives, food industry professionals, farmers, consumers, regional associations, environmental NGOs, Think Tanks, agri-food entrepreneurs, and consultants), share knowledge, and gather feedback on the data–policy link related to FS, BD, CC, and European policies. Through this exchange, a series of main conclusions were collected. These outputs pinpoint areas where progress towards effective sustainability has been made, while also highlighting topics that remain unresolved, requiring further attention and actions.

2. Materials and Methods

2.1. Identification and Analysis of the EU Policies

The identification and analysis of the EU policies related to climate change, biodiversity loss, and ensuring food security were performed by applying two Eklipse knowledge synthesis methods, namely, Method 5, 'Expert Consultation' (https://eklipse.eu/wp-content/uploads/website_db/Methods/Method5_Expert_consultation.pdf, accessed on 20 March 2023), and Method 19, 'Systematic Map' (https://eklipse.eu/wp-content/uploads/website_db/Methods/Method19_Systematic_map-1.pdf, accessed on 20 March 2023) [17]. The 'Expert Consultation' Eklipse Method 5 involved a dialogue with a designated set of experts, either individually or in a group, to gather judgment, evaluations, and/or opinions. This was carried out through online consultations, in-person meetings, individual interviews, written consultations, as well as group meetings. The main source of the specialists in agri-food systems involved in the analysis of the relationships between data and policies has been the Eco-Ready EU Project Partnership. The European Commission's Joint Research Center (JRC) provided access to datasets and all publicly available data in the JRC data catalog, enhancing the ability to scrutinize and comprehend the intricate dynamics of the subject matter. The Confederation of Italian Farmers (Confagricoltura), a key collective organization representing up to 34% of Italian farmers, articulated the legitimate interests of farmers and provided a valuable list of policy documents sourced from their legal experts. The International Union for Conservation and Nature (IUCN), a global authority on nature preservation, contributed expertise in conservation schemes and sustainable development. The Italian National Agency for New Technologies, Energy, and Sustainable Economic Development (ENEA) enriched the analysis with insights into soil health, sustainability, eco-innovation, agri-food systems, and biodiversity. The European Science Policy Interface on Biodiversity and Ecosystem Services (Alternet), deploying Eklipse, synthesized knowledge from diverse sources to inform decision-making on biodiversity, climate change, and food security in Europe. The Cyprus University of Technology (CUT) and Wageningen University and Research (WUR) provided significant inputs, based on their expertise in genetic resource-related policies, contributing to the gathering of documentation and receiving valuable feedback. These inputs were essential for critically assessing policies and ensuring their relevance.

Parallelly, Method 19 'Systematic Map' was based on a structured, stepwise methodology: the systematic search was conducted using a combination of Boolean operators 'AND' and 'OR' to refine the search strategy. 'Climate Change' (CC), 'Biodiversity' (BD), and 'Food Security' (FS) were used as main keywords, and 'Environment', 'Water', 'Energy', 'Health', 'Economic', and 'Society' as secondary keywords were employed to ensure a comprehensive and targeted exploration of the relevant policies in EUR-Lex, the official database of the Publications Office of the European Union. This structured approach ensured the systematic and efficient management of data, allowing for transparent documentation of the search results and facilitating further analysis.

2.2. Analytical Framework

A thorough generic analysis of the screened documents using a two-fold approach involving R scripts and Bibliometrix suite (https://www.bibliometrix.org/, accessed on 5 June 2023) as well as VosViewer (https://www.vosviewer.com, accessed on 5 June 2023) was applied. This approach aimed at extracting insights into the primary keywords within the collected documents and unraveling the connections among them. In total, 101 policy documents resulting in more than 10,000 pages were assessed based on relevant content (Table S1). Keywords were extracted approximately 4500 times based on the frequency of words within each EU document. For the implementation of the R script, the pdftools library was employed (RStudio Version 1.2.5033; R version 3.6.2). Keywords were inspected and harmonized across files and a numeric matrix was generated. The matrix was converted to a binary form, where '1' represented the presence of a keyword, and '0' indicated its absence. The binary matrix was used as an input to create files complying to the .RIS and BibTeX format that were later used for VOSViewer (version 1.6.19) and R Bibliometrix analyses, respectively. After the initial screening, based on the established criteria and the use of Boolean operators 'AND' and 'OR', subsequent sub-screening was implemented to specifically target policy documents. This sub-screening involved filtering the results to include only those documents that contained all three main keywords identified during the systematic search (CC, BD, and FS). Figure 1 summarizes all the steps involved in the methodological pipeline that were followed (Figure 1).

The assessment of the relevant EU policies and the identification of gaps between data and policy was carried out. Drivers were considered as factors that cause change in an ecosystem or a system (natural or human-induced and with direct or indirect effects). As for indicators, they represented measures used to assess the state or trend of a system, providing information about the impact of drivers, and helping in monitoring and managing these impacts (Tables 1 and 2). After the identification of the primary drivers and indicators across the core collection of files, a focused bibliometric analysis was conducted following a similar but more concise data mining and network scheme. Drivers and indicators were regarded as keywords and an R script (pdfsearch library) was employed to screen 22 core EU documents (plus annexes) containing "food security" AND "biodiversity" AND "climate change"; keywords were set before the analysis (Table S2). The R script produced a file (list of keywords per document) that was further converted to the .RIS and BibTeX format. These files were subsequently used for importing to VOSViewer and Bibliometrix suites, respectively, for cluster analyses.

To conduct a thorough analysis of gaps within the screened policy documents, a comprehensive examination was performed to establish links between the identified gaps and pertinent data. Indeed, once the main gaps present in each document were defined, a literature data analysis was performed to offer insights and correlations with data.

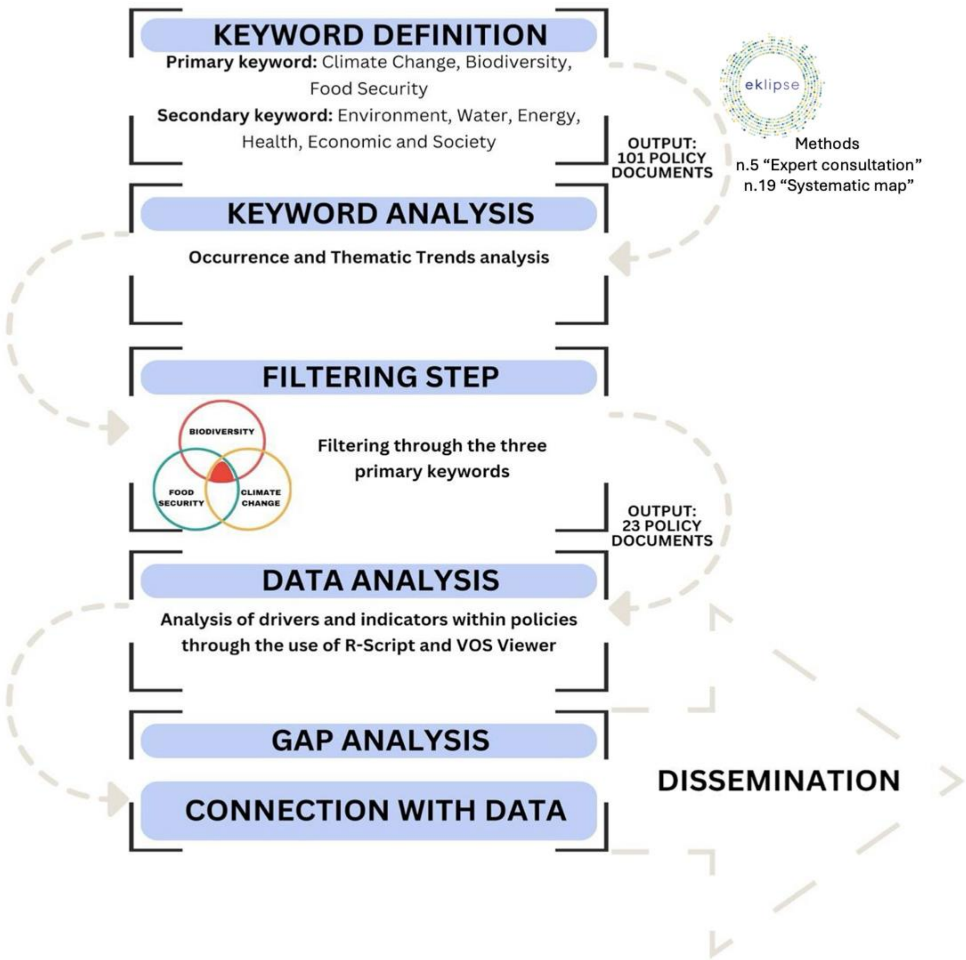

Figure 1. Overview of the methodological approach for screening policies related to FS, CC, and BD.

Table 1. List of drivers related to food security, biodiversity, and climate change.

Dimension	Category	Drivers
Climate Change	Global Warming Ocean Conditions	Global warming, greenhouse gas, methane emission Sea bottom temperature, sea surface temperature, ocean acidification, ocean oxygen depletion, coral reef habitat, algae booms
	Weather Events Atmospheric Conditions Snow and Ice Conditions	Drought, floods, extreme weather events Precipitation, global solar radiation, wind Snow cover, upwelling
Biodiversity	Land Use and Management	Crop rotation, field margin vegetation diversity, afforestation, reforestation, land use, tillage, permanent grassland, field margin type, agroforestry
	Species Diversity	Native crops, invasive species, crop wild relatives, invasive plant species
	Pesticides and Herbicides	Herbicides, pesticides, biopesticides, weed management
	Biological Interactions	Fungi, pathogens, rhizobacteria, pests
Food Security	Nutrient Management	NPKS (nitrogen, phosphorous, potassium, and sulfur), macronutrients, micronutrients, availability for fertilizers
	Agricultural Practices	Herbicides, digital farming, heat stress, organic agriculture, conventional agriculture, soil moisture, pesticide resistance, integrated agriculture, water consumption, precision farming, desalinated seawater use, groundwater availability, groundwater level, groundwater quality, new breeding, seasonal grazing, tillage, river flow, earlier harvesting, antibiotics, water demand, greenhouses, manure, intercropping, cover crops, feed, feed quality

Table 2. List of indicators related to food security, biodiversity, and climate change.

Dimension	Category	Indicators
Climate Change	Greenhouse Gases	CO_2 (Carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), soil emissions
	Temperature and Precipitation	Temperature, precipitation change, Standardized Precipitation Evapotranspiration Index (SPEI), Soil Water Index (SWI)
	Climate and Water	Aquifer sustainability, green blue water
Biodiversity	Species Abundance	Marine biodiversity, bird abundance, spider abundance, bee abundance, insect abundance, predator abundance, parasite abundance, red deer
	Vegetation	Vegetation diversity, floral composition, weed species, dwarf shrub abundance, vegetation height, rough grass
Food Security	Soil Health and Diversity	Soil fertility, soil health, soil indicator, soil moisture, bacterial diversity, fungal diversity, microeukaryote diversity
	Genetic Diversity	Genetically modified organisms (GMOs), inbreeding, genetic diversity, antibiotic resistance gene
	Agriculture	Yield, harvest product, cropping pattern, farm payment, farm labor, farm area average, feed conversion ratio, feed efficiency, energetic balance, self sufficiency
	Economic Indicators	Nutritional value, produce price, product price, producer price index
	Food and Environment	Ecosystem degradation, desertification, soil emissions, non-biotic indicators, carbon cycle, nitrogen cycle, home feeding
	Biodiversity in Agriculture	Earthworm, mycotoxin, weed species, taxa, floral composition, natural enemy richness, dwarf shrub abundance, rough grass, structural heterogeneity

2.3. Scoping Group Activity

To achieve the qualitative involvement of external European policy actors and incorporate their feedback into the ECO-READY project, an ad hoc 'Scoping Group' was established by ENEA with contributions from project partners. This Scoping Group was designed to initiate a consultation process aimed at establishing a continuous dialogue between the project and selected external stakeholders, providing outputs from the EU policy analysis moving from their main field of expertise and investigation. This initiative aimed to ensure coherence between the data collected on policy frameworks, focusing on FS, BD, and CC, and European policies such as the Common Agricultural Policy (CAP) and the Green Deal. A plan was defined to guide the consultation process, which included identifying relevant policymakers, selecting potential invitees, clarifying meeting outputs, defining roles, evaluating partner contributions, and arranging logistics. Invitations were extended to a diverse range of stakeholders, including policymakers from various sectors (EU associations of food industry, farmers, and consumers) and EU organization representative territories, representatives from EU Directorates-General, agri-food companies and NGOs. The first Scoping Group activity occurred in a hybrid format with six experts attending in person (Agro Camera: https://www.agrocamera.com, accessed on 31 October 2024; CUEIM—University Consortium for Industrial and Managerial Economics: https://www.cueim.org/en/, accessed on 31 October 2024; Copa-Cogeca representing farmers and agri-cooperatives in the EU: https://copa-cogeca.eu/?lang=en, accessed on 31 October 2024; ANGA, the National Register of Environmental Managers: https://www.albonazionalegestoriambientali.it/Public/Home, accessed on 31 October 2024; EFFPA, the European Former Foodstuff Processor's Association: https://www.effpa.eu, accessed on 31 October 2024; Assobirra http://www.assobirra.it, accessed on 31 October 2024) and eight online (ACR—Association for Consumer Research: https://acrwebsite.org, accessed on 31 October 2024; ThinkE—Think Europa Institute: https://www.thinke.eu, accessed on 31 October 2024; CLITRAVI—The Liaison Centre for the Meat Processing Industry in the European Union: http://www.clitravi.com, accessed on 31 October 2024; Tecnoalimenti: https://www.tecnoali.com/home-en/, accessed on 31 October 2024; WWF: https://www.wwf.eu, accessed on 31 October 2024; BirdLife International: https://www.birdlife.org, accessed on 31 October 2024; Safe Food Advocacy Europe: https://www.safefoodadvocacy.eu/about/, accessed on 31 October 2024; Italian Government Presidency of the Council of Ministers: https://www.governo.it/en, accessed on 31 October 2024). Preparatory information and guiding questions were set up to facilitate a round-table discussion and dynamic.

3. Results and Discussion

The evolution of European policy documents on FS, CC, and BD not only reflects thematic shifts but also underscores a growing emphasis on sustainability transition and resilience in recent years. In the first screening of 101 policy documents (listed in Supplementary Table S1), in those from 1962 to 2009, the predominant keywords genetics, protection, and policy highlighted an initial understanding of biodiversity and a commitment to protective measures. However, the subsequent period (2010–2018) incorporated complex concepts such as market and conservation, suggesting an equilibrium between economic considerations and conservation efforts, with economic factors becoming key drivers in shaping policies during this period. As the timeline progressed (2019–2021), the emergence of water and biomass underlined an increasing focus on resource management and sustainable energy. In the most recent phase (2022–2023), the keywords environment, biodiversity, and degradation reflected a more holistic approach to environmental challenges and an alignment with the 'One Health' concept (Figure 2). The shift toward sustainability transition suggests a strategic orientation employing practices and policies that promote sustainable development, balancing environmental, social, and economic dimensions.

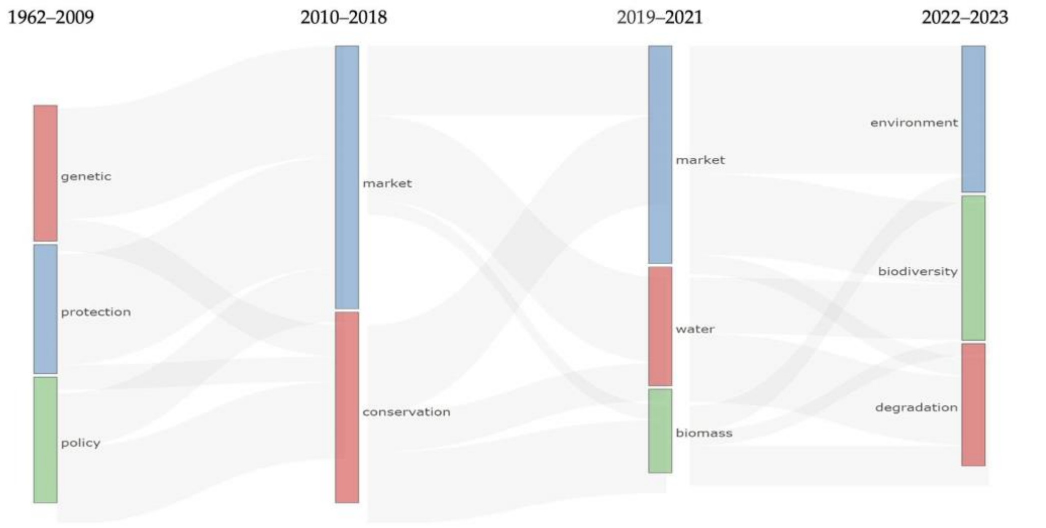

Figure 2. Sankey diagram showing the keyword thematic evolution across time (based on R-Bibliometrix analysis).

The visual representation of keywords in the 23 European sub-screened legislative documents showed crucial topics concerning the impact of climate change and biodiversity on food security. Prominent words were mitigation, yield, greenhouse gas, ecosystems, feed, land use, productivity, related to sustainable agricultural practices and environmental impact management, to strategies to mitigate environmental impact, optimize agricultural yield, and manage land use in the context of evolving ecosystems (Figures 3 and 4).

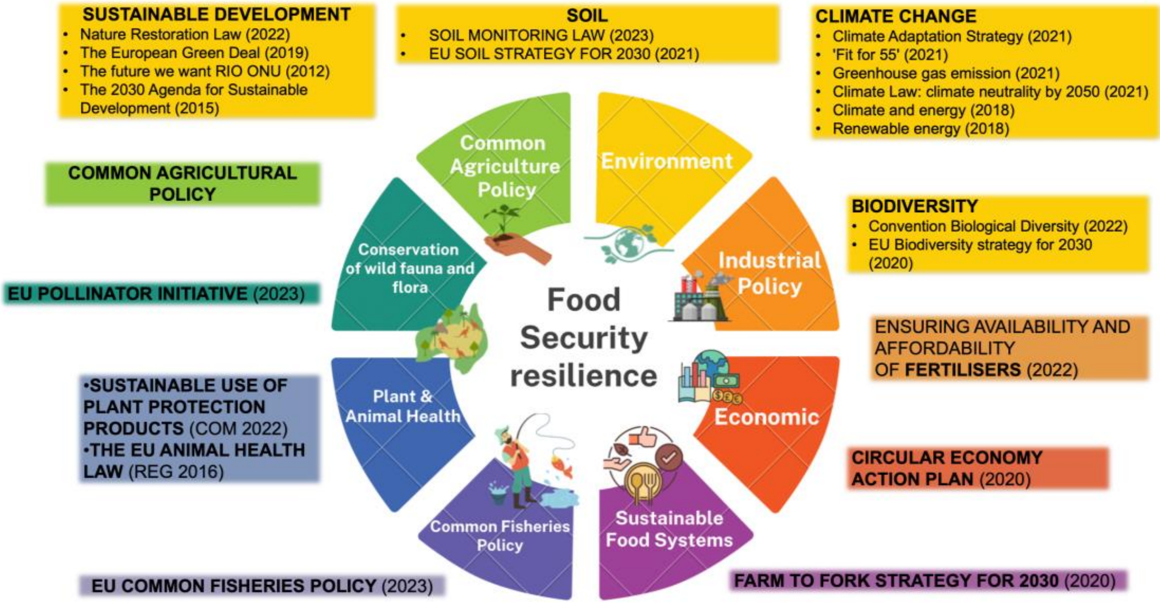

Figure 3. Sub-screened European legislative documents assembled according to EUR-LEX Topic Classification. The number in parenthesis refers to the year of the legislation.

Figure 4. Wordcloud of the sub-screened EU policy (based on R-Bibliometrix suite).

Conversely, in the network map, nodes like ecosystem degradation, One Health, soil indicators, organic agriculture, and sustainable intensification were positioned at the map's edges despite their extreme implications for the climate, environment, and agriculture, suggesting a lack of synchronization to current research outputs, and possible gaps in legislation. Furthermore, terms such as food access appeared outside the map's main core and were not connected with the rest. This marginalization may raise questions about the extent to which environmental policy frameworks comprehensively integrate and address issues related to food access. Given the intricate interconnections and the tug-of-war between agriculture, the environment, and climate, the divergence of food access from the network's main core highlighted an area that may warrant increased attention and consideration within environmental policymaking (Figure 5).

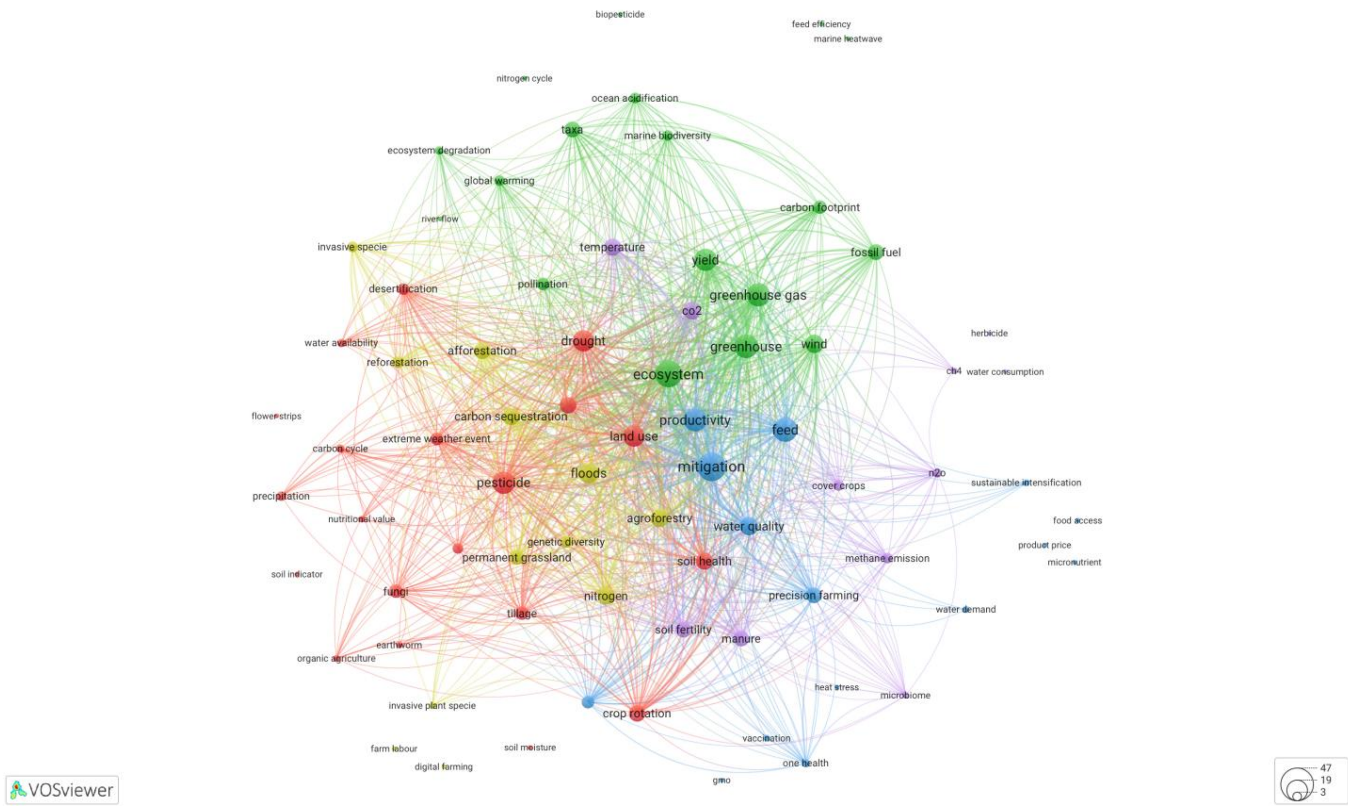

Figure 5. Keyword network map of the sub-screened EU policy (based on R-scripts and the VOSViewer software version no. 1.6.19: https://www.vosviewer.com, accessed on 5 June 2023. The colors represent distinct groups of terms that share a common theme, based on co-occurrences and associations within the textual data, following the Leiden algorithm.

3.1. Common Agricultural Policy: Unraveling the Gaps and Proposing Data-Driven Enhancements for Policy Evolution

In the CAP, several drivers' keywords related to agricultural practices and environmental factors were well addressed. These keywords included terms like global warming, sea surface temperature, precipitation, wind, drought, floods, soil moisture, water consumption, greenhouse gas, afforestation, carbon sequestration, and ecosystem, among others. Drivers related to biodiversity, such as afforestation and reforestation, and correlated to agricultural practices, such as soil moisture and water consumption, were found. The concept of organic agriculture was also thoroughly addressed in the policy.

3.1.1. Enhancing Organic Agriculture and Technological Integration

Organic agriculture is often seen as a pillar of environmental sustainability in European agricultural policies. However, significant critiques exist regarding the efficiency and sustainability of this practice, especially in terms of land use and productive yields. The widespread adoption of organic farming, although responding to a growing interest in responsible consumption and environmental protection, raises questions about its actual capacity to meet increasing food demand without extensive negative impacts on land and resources. Recent studies have highlighted that the yields from organic agriculture are often 19–25% lower than those from conventional agriculture. This productivity gap could lead to greater land consumption, contrary to the objectives of soil conservation and reducing ecological footprints [18]. Another study supports these conclusions, showing that organic farming, despite its benefits for biodiversity and reducing the use of harmful chemicals, might not be able to produce sufficient food for the global population without a significant increase in cultivated land [19]. On the other hand, organic agriculture can play a crucial role in enhancing soil health and preserving biodiversity. A study showed that organic systems tend to improve soil quality, increase biodiversity, and reduce erosion, thus positively contributing to the environment [20]. Enhancing organic farming practices through the integration of technological advancements such as precision agriculture and improved crop cultivars could help in closing the yield gap while maintaining its ecological benefits [21,22]. Policy support for research into sustainable organic practices and incentives for farmers to adopt these technologies could mitigate the negative impacts on land use and ensure that organic agriculture contributes effectively to food security and environmental sustainability. Indeed, organic farming often relies on animal manure as a natural fertilizer, contributing to soil fertility. Animals in organic farming systems are usually treated with antibiotics to ensure their health. Using manure from these animals may introduce antibiotic residues into the soil, potentially contributing to the development of antibiotic-resistant bacteria [23,24]. Moreover, the proposed integration of animal welfare and antibiotic legislation in the CAP Strategic Plan Regulation is seen as a positive step. However, the lack of detailed information and guidelines on how this integration will be carried out may pose a potential gap in the understanding of practical implementations. Spatial restraints that reduce the neighboring of animal and vegetable farms must be considered in order to minimize exposure to fecal microbial agents (*Escherichia coli*, *Salmonella* sp., and *Listeria* sp.) that can cause outbreaks [25].

3.1.2. Integrated Agriculture and Sustainable Practices

A driver that could provide further depth to the policy includes integrated agriculture. This refers to combining different farming practices for better productivity and sustainability. However, despite the absence of the keyword integrated agriculture, some related terms, e.g., crop rotation, are present. Crop rotation plays a crucial role in maintaining soil health: it helps protect soils and preserve their potential by enhancing soil structure, increasing nutrient availability, and reducing erosion [26]. A meta-analysis on diversified crop rotations showed that increasing the crop diversity significantly enhances the soil physical health by improving the bulk density, aggregate stability, and porosity, while also boosting water infiltration rates by up to 20% and soil organic carbon by 10% on average. These benefits, crucial for sustainable water management and erosion resilience, were more pronounced in medium- and fine-textured soils and when combined with conservation practices. However, it is important to underline that the outcomes were influenced by the climate, soil type, and management approaches, thus emphasizing the need for site-specific strategies. Long-term field research is essential for fully understanding and harnessing these improvements, promoting both soil health and agricultural sustainability [27]. Moreover, it has been shown that crop rotation enhances microbial diversity in soils, which is critical for nutrient cycling and disease suppression [28,29]. A meta-analysis of 76 studies investigating the effects of crop rotation on soil microbial indicators revealed increases in microbial biomass carbon (MBC) and nitrogen (MBN) by up to 15% and bacterial diversity (Shannon's index) by up to 8% [30]. Farmers protect soils and preserve their potential through crop rotation. All Strategic Plans include this as a new baseline condition for farmers instead of a new GAEC (good agricultural and environmental conditions) obligation, and rotation will take place on approximately 85% of arable land supported by the CAP. Crop rotations will also help to break disease and pest cycles and the reduce pesticide/herbicide use. Additionally, CAP Strategic Plans will help farmers restore soil fertility, reaching up to 47% of EU agricultural land, for example, through improved crop rotation, conservation agriculture, intercropping, or cover cropping in horticulture [31,32]. While crop rotation is recognized in policy for its benefits, scientific evidence highlights the need for more context-specific strategies. Policies should adapt to varying climatic, soil, and management conditions, providing farmers with the necessary tools and knowledge to optimize these practices.

3.1.3. Indicators and Policy Recommendations

The indicators listed in the CAP cover a wide range of measures used to assess the impact of drivers. These included biodiversity indicators, such as marine and freshwater biodiversity, and indicators for measuring ecosystem degradation and desertification, as well as the carbon and nitrogen cycle. However, indicators that measure the impact of agricultural practices on water quality need to be explored more, being critical factors for environmental sustainability. Other missing indicators referred to the amount of crop produced per unit land area for assessing agricultural performance. It is important to underline that the inclusion of effective drivers and indicators should be based on the specific context and objectives of the policy and should be supported by scientific evidence and stakeholder consultation [33]. Recanati et al. (2019) analyzed 165 papers offering policy recommendations for the future of the CAP. The analysis focused on three pillars: environment, farmers' livelihoods, and citizens' nutrition and health. The study highlighted that the CAP lacked explicit attention to citizens' nutrition and health [34]. Key challenges and improvement areas identified in the literature included the need to maintain financial support for young farmers and/or specific sectors, such as horticulture. This is consistently advocated for to enable better-integrated, participatory, and multidisciplinary research to tailor policies to diverse EU environmental conditions and farming practices, thus supporting knowledge transfer platforms and adopting evidence-based guidelines/policies through integrated evaluation frameworks and databases. Eco-scheme tools are designed to promote practices and approaches such as precision agriculture and organic farming, aiming to enhance sustainability and competitiveness in the food sector. However, to ensure the effectiveness of the CAP in achieving Green Deal targets, robust monitoring and assessment mechanisms are essential. It is necessary to adopt a common data approach and cooperation between Member States and the Commission to guarantee the quality of data for monitoring and evaluation [35]. This reveals a potential weakness in the current system's ability to provide precise and relevant data. The introduction of mandatory standards, such as crop rotation, soil cover, and landscape features, is helpful. Nevertheless, specific details about indicators and baseline levels are needed for a more comprehensive understanding. Eco-schemes emerge as a flexible funding source for environmental and climate action within the CAP. In the CAP's current approach, the role of the Commission may need reinforcement, and new efforts to guarantee data quality implies existing challenges. The effectiveness and benchmarking of eco-schemes hint at potential difficulties in ensuring their success. Also, the fact that they are voluntary means that there is no guarantee about their uptake. Enhancing the effectiveness of the CAP requires integrating market-based, landscape-scale, and food chain approaches that consider local contexts and governance levels. Such approaches promise to improve water quality and agricultural sustainability by fostering collaborations between rural stakeholders and integrating agri-environmental practices throughout the agri-food chain [36,37].

3.2. The Farm to Fork Strategy: Unraveling the Gaps and Proposing Data-Driven Enhancements for Policy Evolution

The F2F Strategy is a fundamental component of the European Green Deal with a vision to establish equitable, healthy, and ecologically based food systems. Central to these strategies are the drivers, which exert a direct influence on agricultural practices and their subsequent outcomes. Important drivers such as the One Health concept, food access, nutritional quality, precision farming, land use, seasonal grazing, inbreeding, antibiotic use, methane emission, animal diet, water quality, and consumer diet were mentioned. Considering the current socio-political situation, the impact of the COVID-19 pandemic, and Russia's conflict with Ukraine, and climatic change pressure on production, the European Union's food system maintains its strength and dependability. However, the European agricultural sector relies on importing essential goods like animal feed, making it vulnerable to future turbulences. The driver animal feed, less extensively explored, is an aspect that should be considered with particular attention in this context due to the farmers experience susceptibility to the elevated costs of inputs such as energy and fertilizers.

3.2.1. Microbial Solutions and Genetic Innovations for Sustainable Agriculture

Built on the One Health concept, F2F should specifically mention the use of a broader range of beneficial microorganisms that could offer innovative solutions for increasing sustainability and efficiency in agriculture, especially in contexts of climate change [38]. These microorganisms, including mycorrhizal fungi and nitrogen-fixing, P-solubilizing, and sulfate-reducing strains of beneficial rhizobacteria (i.e., PGPR), can improve the soil structure, enhance plant resistance to abiotic and biotic stresses, and facilitate more efficient nutrient cycles [39,40]. By promoting the bioavailability of nutrients through processes like phosphorus solubilization and nitrogen fixation, these organisms reduce crop reliance on chemical fertilizers. They also synthesize growth-promoting compounds that aid in plant development and employ mechanisms for biocontrol, such as producing siderophores that limit iron availability to pathogens, thereby enhancing plant health and disease resistance. Arbuscular mycorrhizal fungi, as natural root symbionts, significantly contribute to plant nutrition, thereby improving plant tolerance to environmental stresses and enhancing soil fertility. Additionally, recent studies have explored the role of endophytic microorganisms, which live inside plants, in promoting plant growth and improving disease resistance [41]. Building on the benefits of diverse microorganisms in agriculture, the concepts of functional equivalence and functional redundancy further underscore the potential for resilience in farming systems [42]. By fostering a variety of beneficial microorganisms that can fulfill similar roles in the ecosystem, agriculture can maintain productivity and stability even when faced with environmental stresses and also suppress soil phytopathogens without chemicals. The strategic use of these microorganisms in agriculture could maintain productivity and stability even under adverse conditions, thus enhancing the adaptability of farming practices to changing climates [24]. Moving from drivers to indicators, which operate as critical measures for evaluating the impact and performance of agricultural practices, while the policy addresses water-related issues, an explicit remark on water consumption and desalinated seawater use is central for agriculture sustainability and would serve to accentuate the urgency of optimizing water use, especially in an era when freshwater resources are becoming increasingly limited. In Europe, particularly in the Mediterranean region, sustainable water management is essential to mitigate the escalating ecological drought exacerbated by population growth, economic activities, and shifting consumption patterns, with non-conventional methods like desalination and wastewater reuse emerging as key solutions to freshwater scarcity [43]. Another indicator that requires further investigation is the potential role of GMOs in addressing environmental sustainability and agricultural resilience. The European Union policies that prevent the introduction of GMOs and gene-edited plants ignore the potential of these technologies to provide greater resilience by allowing the maintenance of yields and quality with reduced chemical inputs and less adverse environmental impacts in the context of emerging challenges from climate change. Current policies may need to be revised to explore how GMOs can effectively support environmental sustainability goals through improved agricultural practices. Genetically modified crops offer possibilities to reduce resource consumption and improve agricultural yields, thus contributing to the reduction in chemical inputs and enhancing agricultural production efficiency [44,45]. Despite these potential benefits, concerns about biodiversity and human health continue to dominate the debate over GMOs in Europe. Studies have explored these concerns, suggesting that with appropriate regulatory and monitoring regimes, the negative effects can be minimized, thus allowing the benefits of GMOs to be harnessed without compromising safety and environmental integrity [46]. In the 2020s, a new “gene revolution,” whereby DNA can be genetically edited without splicing in genes from a separate organism, so-called “genome-editing”, has emerged to enhance the resilience and nutritional content of various crops, by combatting biotic and abiotic stresses, helping mitigate the effects of climate change on agriculture [47]. The potential benefits of gene-edited crops include higher yields, improved resistance to pests and pathogens, and reduced reliance on pesticides. In 2021, the European Commission officially proposed the loosening of the rules on the use of new genetic techniques (NGTs) in farming, paving the way for gene-edited crops for food to be found on EU citizens' plates soon. On 5 July 2023 (European Commission, 2023. Proposal for a new Regulation on plants produced by certain new genomic techniques. https://food.ec.europa.eu/plants/genetically-modified-organisms/new-techniques-biotechnology_en, accessed on 12 September 2024; European Commission, 2023. Proposal for a regulation of the European Parliament and of the Council on plants obtained by certain new genomic techniques and their food and feed and amending Regulation (EU) 2017/625. European Commission. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0411, accessed on 12 September 2024), the European Commission published a draft regulation on plants obtained by certain new genomic techniques aiming to exempt NGTs from GMO regulations if the changes made could have occurred through conventional breeding methods.

3.2.2. Governance Challenges and Implementation Success

Even if the F2F Strategy is recognized as a significant step in European food policymaking with the goal of creating a fair, healthy, and environmentally friendly food system, the success of the strategy depends on resolving key governance challenges and maintaining political momentum during implementation. The strategy lacks a clear definition of food sustainability or a sustainable food system, making it an ambiguous concept. The European Commission stressed the environmental, health, social, and economic benefits without providing specific boundaries. The broad interpretation of food sustainability poses a risk of policy incoherencies, as actions supporting one objective may hinder others. F2F's success depends on addressing substantive and institutional challenges, e.g., involving stakeholders to strengthen its social basis [1]. Food democracy initiatives, such as food policy councils or citizen summits, are seen as promising for navigating conflicts of interest and values. The strategy's success depends on political support from the European Parliament and Council, reconciling opposing interests, and considering the economic challenges following the COVID-19 pandemic.

3.3. Addressing Food Security in the Context of Climate Change and Biodiversity Loss

3.3.1. The Role of the EU in Biodiversity and Challenges in Conservation Objectives

The EU has made significant efforts to address biodiversity loss, pollinator decline, and sustainable agricultural and marine practices, aligning these goals with the European Green Deal. The EU Pollinator Initiative aims to reverse the decline of wild pollinator populations by 2030, recognizing their critical role in contributing over 5 billion euros annually to the EU's agricultural output. However, the world is experiencing a severe loss of pollinators, which threatens both ecosystems and human well-being. Protecting pollinators is essential for preserving biodiversity and agricultural health. Animal pollination is vital for many food crops, ensuring both food security and nutrient diversity, but the decline in pollinators, coupled with the global rise in pollination-dependent crops, poses a growing risk to agricultural yields and food availability [48]. The Common Fisheries Policy seeks the long-term sustainability of fishing and aquaculture activities, ensuring food security and protecting marine environments. Considering ongoing environmental changes, particularly in climate change hotspots like the eastern Mediterranean, current conservation objectives that focus on native species may become less viable. Native species in these regions face the risk of local extinction or severe competition from invasive species. Conservation policies must therefore become more flexible, prioritizing the preservation of ecosystem functions rather than individual species. This adaptability is crucial in responding to biodiversity changes driven by global warming, ensuring that ecosystems remain resilient [49]. The Common Fisheries Policy aims to ensure the long-term sustainability of fishing and aquaculture activities, preserving the socio-economic fabric of coastal communities and contributing to the protection of the marine environment. Specific considerations on key drivers and indicators, such as seafloor temperature, salinity, marine and freshwater biodiversity, and predator abundance, would allow for a holistic approach to marine resource management. The BD- and CC-related policy analyses underscore the necessity of integrating specific considerations regarding the nutritional quality of crops, insect abundance, and sustainable management of marine resources to promote more effective management of marine ecosystems, fishery resources, and agricultural practices. This integration can contribute to the conservation on biodiversity and environmental sustainability. The multifaceted effects of climate change significantly influence various ecosystems and agricultural systems, necessitating a comprehensive assessment of these impacts. For instance, research from Lake Vembanad in India has shown the importance of adopting climate-resilient strategies to protect aquatic ecosystems [50]. Another study explored potential compliant strategies for 29 crops in sub-Saharan Africa in response to future climate changes, providing important insights into possible adaptation strategies to preserve agricultural productivity and food security in the context of climate change [51]. Additionally, research in North America has demonstrated how glacier retreats are creating new habitats for marine species, such as Pacific salmon, further illustrating the complex relationship between climate change, adaptability, and biodiversity [52]. A comprehensive understanding of the impacts of climate change on nutritional quality was illustrated by a study that examined how climate change is influencing the fragmentation of Florida stone crab communities, underscoring the importance of considering environmental impacts on marine species [53]. Additionally, a recent study examined the productive and reproductive performance, behavior, and physiology of livestock under heat stress conditions, elucidating the direct impacts of climate change on agricultural production and animal health [54]. Another study reported the effects of environmental conditions and jellyfish blooms on pelagic fish and fishing activities in the Western Mediterranean Sea, underlining the impacts of climate change on fishery resources and the fishing industry [55]. By leveraging data-driven insights, it is feasible to understand the complex interactions between ecosystems, agriculture, and biodiversity, providing essential guidance for developing effective adaptation strategies and long-term resilience against the challenges posed by climate change. The EU has made substantial attempts to cope with land and water biodiversity loss and to align these goals with the European Green Deal and several scholars have analyzed the policies' impact. In that sense, Pettersson et al. [56] discussed the interplay of legal and policy frameworks for biodiversity protection, particularly under the prism of climatic change, while Kluvánková-Oravská and colleagues [57] highlighted the caveats of policy convergence in the Europeanization of biodiversity governance due to the ongoing EU enlargement. On the other hand, Klassert et al. [58] focused on improving policy blending by evaluating existing tools under the Birds and Habitats Directives and the Common Agricultural Policy. Their analyses stipulated that the authority distribution among the EU Commission and EU members offers discrete comparative advantages for the introduction of market-based instruments across the different policy disciplines. More recently, Overmars et al. [59] delved into developing a method for species-based and spatially explicit indicators of biodiversity documentation on EU agricultural lands. Also, Egloff and coworkers [60] provided a data–policy framework to utilize biodiversity data within the EU BON project and address concerns such as mobilizing data and eliminating legal obstacles. Parallelly, Schulp et al. [61] performed a quantitative assessment of policy options for achieving "no net loss" (NNL) of biodiversity or/and ecosystem services within the EU states. Indeed, the notion of NNL and its related tools to attain them have been extensively discussed in the literature [62–64]. While biodiversity offsets have been widely criticized [65], they have received more attention than avoidance, reduction, or restoration measures [66,67], which are the focus of most current NNL policies and are most relevant for conservation objectives. Furthermore, although the majority of research on NNL concentrates on species and habitats of the greatest conservation concern, common species contribute disproportionately to ecosystem biomass and functions, and losses of biodiversity and ecosystem services are not restricted to endangered species or protected habitats [68]. Accordingly, NNL strategies must be evaluated in light of a broad range of biodiversity and ecosystem services rather than only endangered species or habitats [69–72]. The significance of further efforts to operationalize the NNL aim of the (Biodiversity) Strategy for places and species not covered by current EU nature law has also been emphasized by the EU Environment Council of Ministers.

3.3.2. Strategic Planning for "Biodiversity Adaptive Management"

The achievement of the ambitious objectives outlined in the biodiversity-related policy documents centers on the ability of EU Member States to strategically plan the implementation of conservation measures within constrained and uncertain budgets. Additionally, successful implementation requires improved engagement with the public and the prevention or resolution of potential conflicts with other socio-economic objectives and sectoral policies. All these efforts must be optimized amid the recovery from the adverse social and economic impacts of the COVID-19 pandemic. To efficiently implement policies such as the Biodiversity Strategy for 2030, a crucial initial step involves recognizing the strengths and weaknesses of past biodiversity management experiences, identifying gaps, and building upon previous initiatives. Adequate planning is instrumental in addressing historical weaknesses in EU policy, such as the inadequate distribution of limited conservation funds, and conflicts between biodiversity conservation and opposed interests. The challenges posed by global change and its dynamic conditions necessitate adaptive biodiversity management [49]. Effectiveness in biodiversity conservation management requires adaptability to respond to these dynamic conditions. In certain cases, management beyond protected areas becomes essential to enhance the effectiveness and resilience of conservation efforts in the face of global change. Policy and funding mechanisms exist to support biodiversity management beyond protected areas, including the establishment of the future network of Green Infrastructures and High Nature Value Farming in agricultural land [73,74]. However, past experiences underscore the need for careful planning in the implementation of these strategies to minimize potential conflicts with other sectoral interests/priorities. The improved integration of biodiversity conservation into other sectoral policies and funding mechanisms is crucial to overcoming past failures. Collaborative efforts, not only financial but also in terms of governance and multi-sector integration, are essential for achieving common goals. Without such collaboration, the future implementation of EU nature policy is at risk of repeating past mistakes and failures. Certain needs, not explicitly addressed in current policies, demand urgent attention to guide Europe towards biodiversity preservation and recovery, and more sustainable development. This proactive approach could also reinforce the EU's role as a global leader in biodiversity conservation, setting an example for halting biodiversity loss in other regions worldwide amidst the global biodiversity crisis. This strong leadership is essential for shaping international agenda in the coming decades, including the negotiation and implementation of new international agreements, such as the Convention on Biological Diversity, with the aim of halting biodiversity loss.

3.3.3. Exploring Opportunities and Understanding Climate Change Impacts

In several policies, such as the Circular Economy Action Plan and Renewable Energy Legislation, key aspects related to agricultural and food sustainability have not been thoroughly addressed. For instance, precision farming, which employs advanced technologies like GPS and data analysis to optimize agricultural production while reducing environmental impacts, has not been exhaustively addressed. This practice could play a crucial role in promoting more efficient and sustainable agricultural systems. The transformative potential of advanced technologies for precision farming, such as GPS and data analytics, in revolutionizing agricultural efficiency while minimizing ecological footprints has been underscored [44,75]. The policies' missed opportunity to explicitly integrate precision farming techniques represents a substantial setback in fortifying agricultural sustainability and environmental protection [76]. Additionally, a detailed analysis of the nutritional value of agricultural products and the integration of crop wild relatives (wild species genetically linked to crops) requires more attention, being essential for improving food quality and developing crop varieties resilient and adaptable to changing environmental conditions. Castañeda-Álvarez et al. (2016) describe the importance of nutritional value in agricultural produce and advocate for leveraging crop wild relatives to fortify crops against environmental adversities [77]. Implementing more sustainable agricultural policies needs a comprehensive approach that includes the responsible use of fertilizers and pesticides, optimal soil management, and the promotion of agricultural practices preserving biodiversity and soil fertility. Indicators like the carbon cycle and water consumption have not been sufficiently focused. The carbon cycle, representing the interconnection between carbon emissions and absorption in the environment, is crucial for understanding the impact of human activities on climate change and environmental stability [78]. Furthermore, the lack of a detailed focus on water consumption, sustained by robust data and early warning measures to be adopted concerning responsible water resource use, is crucial to ensure water resource sustainability and aquatic ecosystem conservation [79]. The impact assessments also highlighted the necessity of the continued implementation, monitoring, and, if required, refinement of existing policies. This convergence of policies, grounded in scientific evaluations and global commitments, forms a holistic framework necessary to address the urgent challenges of climate change, resource depletion, and sustainable development.

3.4. Insights from the Scoping Group: Addressing Gaps in Data and Drivers for Food Security Policies

The proceedings from the Scoping Group revealed that understanding the drivers and data supporting European policies, particularly concerning food security, is complex and multifaceted. Stakeholders expressed the necessity for better involvement in policy generation processes and discussions, highlighting that all members of the agri-food supply chain should be better considered to accurately identify the diverse drivers and datasets that warrant consideration by European legislators. The interplay between these elements is critical, especially as they influence the allocation of funds for the 2014–2020 programming period and the future cohesion policy post-2027. The participants agreed upon the main conclusions presented by the Eco-Ready consortium before the Scoping Group and emphasized the importance of qualitative data collection, identifying challenges and drivers that can highlight territorial fragility and guide the concentration of resources effectively. There is an urgent need for enhanced data to support evidence-based policies, necessitating the localization of food security strategies at various governance levels. Additionally, new developments, such as the rise in direct sales during the pandemic, must be better understood to inform territorial policies effectively. The current landscape of data collection is hampered by varying definitions and methodologies, leading to inconsistencies that can misguide policymakers. Notably, still-existing gaps were identified in the collection of primary data available from agri-food farmers, essential for creating comprehensive "ecosystem" datasets to inform future policies under initiatives like the Farm to Fork Strategy and the Green Deal. Fostering greater agri-food supply chain member involvement is essential, as a lack of trust and the non-mandatory nature of data collection is still limiting effective collaboration, especially if they are considered as separated blocks. Overall, the Scoping Group, in line with the Eco-Ready project philosophy, confirmed that a greater and wider positive impact will be achieved, in terms of active involvement, if the different actors collaborate in a supply chain approach, where each respective role and the contribution is linked from Farm to Fork. In addition, the data and drivers analyzed by the Eco-Ready project can assume higher value and representativeness as much as they can also include competitiveness as an enabling factor to allow better and smoother collaboration between agri-food farmers and producers. Also, the Scoping Group activity revealed the main role of policy actors, stakeholders, and researchers in favoring the transition towards food security resilience against climate change and biodiversity loss. A more integrated approach to data and drivers is necessary to ensure that policies can effectively support a fair and sustainable transition for all sectors within the agri-food system by including a socio-economic–environmental assessment. Finally, in order to comply with the objective of better and effective collaboration and awareness amongst agri-food supply chain actors, capacity building and knowledge transfer actions offered by national and EU research centers could play a key role, especially when it comes to gathering and refining qualitative and quantitative information along the value chain.

4. Conclusions

Considering the gaps and the challenges that our agri-food system is facing, the synthesized findings in this work suggest the urgent need for real-time and early warning monitoring tools for food security, along with scenario models that account for the complexity of technical, economic, and social conditions, going beyond general objectives to consider tailored solutions. Recognizing drivers and indicators as key concepts, the results encourage landscape-specific approaches to maximize biodiversity gains from agricultural practices, mitigate climate change effects, while assuring food security. For example, the promotion of remote sensing technologies, exemplified by Copernicus Sentinel-2 data, is crucial for enhancing the monitoring of agricultural activities. Moreover, it is important to underscore the significance of emerging ICT technologies, such as the Internet of Things (IoT), Artificial Intelligence (AI), and Cloud Computing, in facilitating real-time information exchange throughout the farm-to-fork value chain. The call to action includes the promotion of green infrastructure implementation and an increased focus on the 'One Health' concept. Addressing issues related to food security within the context of climate change and biodiversity loss, considering factors like poverty, conflicts, and post-pandemic challenges, is essential. While acknowledging the pivotal role of large-scale farmers, the equal consideration of the needs of small farmers to ensure inclusive and sustainable agricultural practices has to be considered in the CAP. Moreover, the relationship between data/drivers and food security policies is crucial for allocating funds in the closing programming period (2014–2020) and future cohesion policies post-2027. Collecting qualitative data and identifying drivers and challenges are essential for optimizing EU and national budgets. Food security drivers can highlight territorial fragility, necessitating a focus on resource concentration. Challenges include the need for more localized, diverse data, overcoming limitations in data definitions and methodologies, involving the private sector, and linking scientific approaches to economic growth variables for a fair transition to sustainable agri-food sectors.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/su162310749/s1: Table S1: Policy document list from the search involving the Expert Consultation and Systematic Maps approaches; Table S2: Core EU policy documents containing the terms 'food security', 'biodiversity', and 'climate change'. The table lists policies where all three keywords were present.

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