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Review article

The water-energy-food nexus in biodiversity conservation: A systematic review around sustainability transitions of agricultural systems

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A R T I C L E I N F O

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A B S T R A C T

The Water Energy Food nexus is a powerful topic in agricultural systems to elucidate threats to biodiversity conservation and culture. This paper aimed to recapitulate nexus thinking research, focusing on social-ecological transitions of agriculture systems and biodiversity management within the Water-Energy-Food nexus. We developed a systematic review and a bibliometric analysis derived from 529 documents in the Scopus database. The ToS method identified a total of 81 relevant information in the sample of documents (529) categorised into roots (10), trunks (9) and leaves (62). This review paper situates types, focus, and highlights regarding biodiversity and prevalent thematic research areas such as "Food Nexus", "Environmental Flows", "Sustainability", "Transitions", and "Governance". Our results suggest that future research should focus on the nexus of "Water-Energy-Food-Biodiversity" and propose a transdisciplinary approach to elucidate the state of sustainability transitions in the agricultural systems at the landscape level. It could increase stakeholder interest in conservation, and sustainability management, to reverse biodiversity losses in ecosystems.

1. Introduction

Strategic ecosystems are threatened mainly by human activities in addition to geological [1] and climate change phenomena [2]. Evidence shows how agricultural systems exceed planetary boundaries [3] condition the scope of the SDGs [4] and generate an accelerated loss and transformation of biodiversity [5]. The idea of keeping human activities within planetary boundaries [6] due to the risks posed by unsustainable production and consumption calls for conceiving sustainable development trajectories in organisations and incorporating planetary boundaries into planning processes [7].

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At first sight, social-ecological systems and human-environmental systems interface in organisational levels, space, and time dimensions are fundamental to addressing complex interconnections and identifying structured solutions to key global sustainability challenges [8]. Recent scientific research on transforming food systems identifies the requirement of rerouting farming and rural livelihoods to new trajectories that reduce emissions, are climate-resilient, and implement nature-based solutions [9,10]. The relationship between ecosystems, livelihoods, and the economy together with the water, energy, and food nexus thinking, are becoming a major academic research area [11]. This system-thinking approach recognizes links between policy and decision-making to articulate them and minimise negative externalities and unexpected consequences in addressing common challenges, from the local to the global scales [12].

When the World Economic Forum published the Global Risks report [13], the modern concept of the Water-Energy-Food nexus became mainstream to address the inseparable links between resources and variables such as environmental pressures, economic and population growth, global governance failures, and even geopolitical conflicts [11]. Evidence of this is seen through the degradation of ecosystems and biodiversity losses [14], pollution in soil [15], oceans and freshwater [16] generated unproductivity in ecosystems [17], and agricultural lands. We are now aware that modern agriculture is not sustainable because meeting humanity's growth for food demands, biofuels, and materials in the 20th century could lead to drastic changes in agricultural Systems defining our time to meet the growing needs in the energy-water-food nexus without compromising the capacity of the next generations [18].

To deal with challenges in agricultural production systems, nexus research presents an alternative as it integrates social, economic, technical, and ecological criteria into the multi-scale analysis of societal and ecosystem metabolism [19]. Long-term thinking is needed in agricultural development and nexus thinking becomes a tool to fully assess interactions at varied levels in agri-food systems. The social, economic, and political aspects of the WEF nexus need to be addressed in order to link this systemic approach to effectively advise on sustainable development [20] and support decision-making processes regarding underwater security conditions and climate change [21]. Therefore, it is recognized that all the seventeen SDGs are connected and that developments in one sector will impact other sectors [22]. Thus, any proposed sustainable development in agricultural systems must balance socioeconomic and environmental sustainability.

Studies have pointed out that to effectively guide nexus governance, a co-production of the nexus analysis involving diverse social actors and more complete datasets at the river basin level is strategic [19,23]. Interestingly, integrated natural resource management is emerging as an avenue through which agricultural research can increase rural prosperity and policy change overcoming various stages including denial, re-knowledge, analysis, innovation, scenario synthesis, and platform policy creation [24]. There is an agreement in the scientific community and policymakers that biodiversity, water, and energy are structurally important for food production. Therefore, the nexus approach serves to achieve efficient outcomes and guarantee sustainable resource use [25].

The Latin American and Caribbean (LAC) countries have not yet incorporated the nexus approach in policy design, planning, regulation of public services, or management of natural resources. This confirms the importance of improving the inclusion of demographic, geographic, economic, and quality of governance variables in heterogeneity circumstances, implying a differentiated treatment at the country and sub-country levels [26]. There is considerable research [27–29] on relationships in the WEF nexus and pathways for responsible agriculture and food systems transformation. However, the literature does not provide conclusive insight into the applicability of sustainability transition scenarios related to biodiversity conservation.

Researchers [8,24,30–32] have provided evidence on environmental pressures, human and ecosystem health issues, and the importance of landscape restoration actions under the planetary boundaries' framework in human-nature interactions along the supply chain. Nonetheless, the use and flow of resources in the WEF-Biodiversity nexus that agri-food systems must make within sustainable transition scenarios have not yet been elucidated. The nexus thinking has been analysed and criticised [33]. Firstly, actions on nexus have largely remained in the water sector, and although it emphasizes trade-offs, investments, policies, and governance aspects of the interconnections between food, water, energy, and the environment. A challenge remains to map this approach onto current governance structures and implement it in a systematic manner. Nexus thinking requires policy and practical reforms (e.g., changing technology, knowledge, cross-sectoral market strategies, and governance regimes). Thus, straightforward pathways are not yet clear for implementation.

This paper aimed to recapitulate nexus thinking research, focusing on social-ecological transitions of agriculture systems and biodiversity management within the Water-Energy-Food nexus. To the best of our knowledge, no analysis of the trajectory of nature's benefits to people use and flow in the Water-Energy-Food-Biodiversity nexus that agri-food systems should make in scenarios of sustainability transitions related to biodiversity conservation has been elucidated.

Nexus methodologies have catalysed improvements in nexus scenarios simulation on population, anthropogenic pressures, and recently sustainable food production governance. Evaluating this data specifically focusing on the sustainable transitions in agri-food systems to activities compatible with the conservation and sustainable use of biodiversity will provide valuable insights into the relationships among the use and benefits of biodiversity, quality of life and governance, and contributions of nature-based solutions to sustainability transitions in the WEF-biodiversity nexus.

Our study provides valuable contributions to the literature regarding the research and application of the WEF - Biodiversity nexus in sustainable transitions of agri-food systems. Firstly, it carries an analysis of scientific publications in the WEF nexus by document type, citation networks, and the most relevant application topics addressed in the nexus. Secondly, it performs a classification of the literature reviewed according to specific nexus categories, focus, highlights, and keyword co-occurrences network for application in agri-food systems. Thirdly, it analyses the importance of biodiversity in the nexus analysis required for sustainable transitions in agricultural systems parting from the water-energy-food-biodiversity nexus.

We aim to outline and consolidate the knowledge base of the current state of research through this critical review and further provide an expanded and comprehensive analysis of the nexus challenges and practical implications for nexus assessment in biodiversity conservation.

2. Methods

2.1. Bibliometric analysis

A systematic literature review on the Water-Energy-Food nexus and biodiversity conservation according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) protocol was conducted [34–36]. We carried out the bibliometric analysis of indexed data in Scopus (scopusWEF.bib) focused on humanities and interdisciplinary studies screening publications until 2021 (1annual_pccion_data.csv). A targeted search for meaningful documents had been set for February 2022. We created a search equation on the representative themes of the WEF nexus related to biodiversity conservation and sustainability transitions in agriculture. The syntax used corresponds to ("water" AND "energy" AND "food" AND "nexus") AND ("biodiversity" OR "ecosystems" OR "environment" OR "ecosystem services") and was applied as a fundamental search on titles, keywords and abstracts of data indexed in Scopus. The process of article selection included time limits between 2009 and 2021, knowledge subareas with a greater impact on the field [34,37], removing editorials and trade journals, and excluding Chinese and German language [38]. Altogether 529 publications and their cited references were collected and exported CSV file, and Txt file. In addition, we included the thematic axes and research contributions by country (General data. xlsx).

In line with existing research studies [38–41] it has been applying a bibliometric technique to develop a network analysis. Data were analysed using VOS viewer bibliometric software following the approach proposed by van Eck and Waltman [42] to identify and analyse developmental trends, countries' co-authorship, authors' co-citation, and keywords co-occurrence (2author_pccion.csv, savedrecs2.txt). VOS viewer was used to draw out the terms from the title and the abstract of each document of the sample obtained through Scopus database (529 documents – scopus529.cvs). A total of 876 terms were identified by composing the bibliometric sample of this review study. A subsequent step included data processed using the criteria: (a) At least 2 occurrences and (b) Filtering out irrelevant and repetitious data. Finally, the co-occurrence map was designed with 49 items and 8 clusters.

2.2. Tree of science – ToS

We have found relevant literature on the web-based tool (https://coreofscience.shinyapps.io/scientometrics/tos.coreofscience.org) Tree of Science (ToS) that uses graph algorithms to optimise the search. ToS was created at Universidad Nacional de Colombia, shows the results in the form of a tree: root (the classics), trunk (structural publications), and leaves (current publications), and uses scientometric techniques to recommend relevant literature [43–47]. Drawing from 529 publications and their cited references collected in VoS viewer bibliometric software in the BibTexfile (scopus WEF.bib) we assessed publications according to three indicators: indegree, intermediation and outdegree. Consequently, the ToS software has identified high-input and zero-output as roots, high-intermediate items as trunks, perspective-determining items as branches, and high-output and zero-input information as leaves, adding a tree perspective. The method identified a total of 81 relevant information (Tos 81.cvs) in the sample of documents (529) categorised into roots (10 documents), trunks (9 documents, and leaves (62 documents). The Pearson Chi-squared test was applied to assess differences in Ref. [48] the documents analysed in the review.

3. Results

3.1. Bibliometric analysis - water-energy-food-biodiversity trends

This section presents the contributions of the 529 documents identified by the Scopus database for the terms WEF nexus and biodiversity (Fig. 1) in the period between 2009 and 2021.

The papers were distributed into 13 thematic axes according to the Scopus review in environmental science, social sciences, energy, engineering, agricultural and biological sciences, and earth and planetary sciences (302, 110, 84, 72, 68, and 52 respectively). The most contributing countries (Fig. 2) were the USA, UK, China, Germany, Italy, Australia, Netherlands, and India (188, 99, 64, 48, 46,

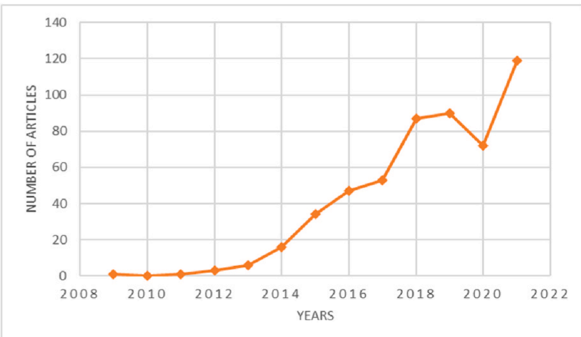

Fig. 1. Frequency of annual scientific publications on biodiversity-water-energy-food-biodiversity nexus research during 2009–2021 (n = 529).

38, 37, and 22 respectively).

From South America, there was a low percentage of contributions, limited to Mexico, Ecuador, Argentina, Chile, and Brazil. The low contributions of papers led by Latin American countries should be a cause for concern given the strategic importance of the WEF nexus to biodiversity conservation in this geographical region. The most subject area consulted was Environmental Science followed by Social Sciences, Energy, and Agricultural and Biological Sciences.

3.1.1. Network analysis

As shown in Fig. 3 we generated through the VOS viewer tool the network map related to the co-authorship between countries of the 529 documents identified by the Scopus database.

Fig. 3 depicts a strong country co-authorship particularly from 2018 to 2021 of the USA, England, Netherlands, and China. In 2018 represented by the purple cluster Germany has contributed principally with Australia, India, Austria, and Ethiopia. The USA, assigned to the blue cluster, in 2019 represented collaboration with China, Netherlands, France, and Mexico. England in the green cluster has collaborated with Spain, Equator, Philippines, and Japan in 2020. Recently, in 2021 Finland, Nepal, Ireland, and Lithuania had a strong collaboration with the USA, Netherlands, China, and England. The period with the strongest co-authorship around the world corresponds from 2019 to 2020.

Co-citation analysis paired documents that were similarly cited and allowed recognition of research fronts [41,49] in the nexus WEF-Biodiversity. Fig. 4 displays three distinct clusters of red, blue, and green nodes denoting references with a common intellectual base but different subfields. Pfister [50] founded the red cluster in 2009 considering health, ecosystem quality, and resources around the relative impact of water consumption including water-intensive products, such as agricultural goods. The importance of assessing the environmental footprint in supply chains to understand the sustainability, efficiency, and equity of resource use from the perspective of different stakeholders along the chain was pointed out by Hoekstra and Wiedmann [51]. In this regard, Vanhman [52] contributed to the understanding of WEF-ecosystem nexus showing the links between available water resources (green and blue), food security, and water for environmental flows or other ecosystem services.

As shown in Fig. 4, this understanding was adopted in the green cluster by D'odorico [53]. This paper highlights the central concern around the environmental pressures of food production. Themes addressed included Planetary Boundaries [6,32] and SDG's as possible approaches to meet resilient food security, and sustainable agriculture. Research in this cluster explored how trade-offs and synergies of the three resources could decrease vulnerability to climate change but generate disaster and environmental degradation in the long term [54].

Additionally, the blue cluster nodes that appear with Hoekstra and Mekonnen [55] associated the magnitude of the human water footprint with two factors, the volume and pattern of consumption and the products consumed, which in the case of agricultural products, is contingent upon climate, irrigation and fertilisation practices and crop yields. Mekonnen and Hoekstra [56] considered that the water footprint of any animal product is larger than the water footprint of crop products with equivalent nutritional value. Approximately 29% of the total water footprint of the agricultural sector globally is related to animal products, where beef cattle production accounts for one-third of this footprint [57].

Scientific research signalised three clues for reducing the threat posed by water scarcity to biodiversity loss and human well-being. Keeping water consumption within maximum sustainable levels per river basin, increasing water use efficiency in agriculture, and improving the share of limited freshwater resources [56]. Furthermore, Dalin [58] performed an approach to the groundwater depletion index worldwide, identifying regions, crops, and trade relationships most dependent on overexploited aquifers. This

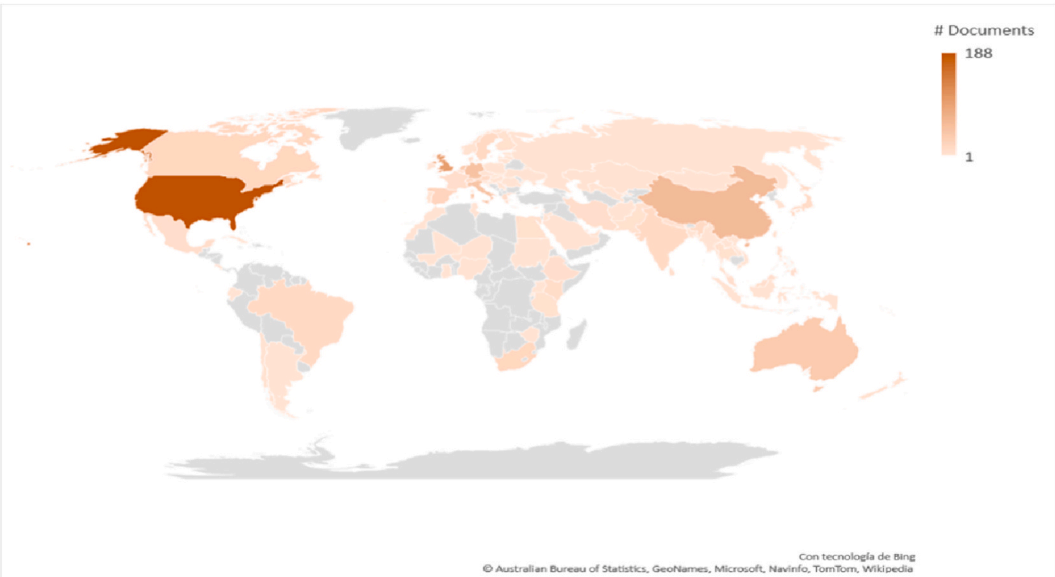

Fig. 2. Geographical distribution of paper contributions.

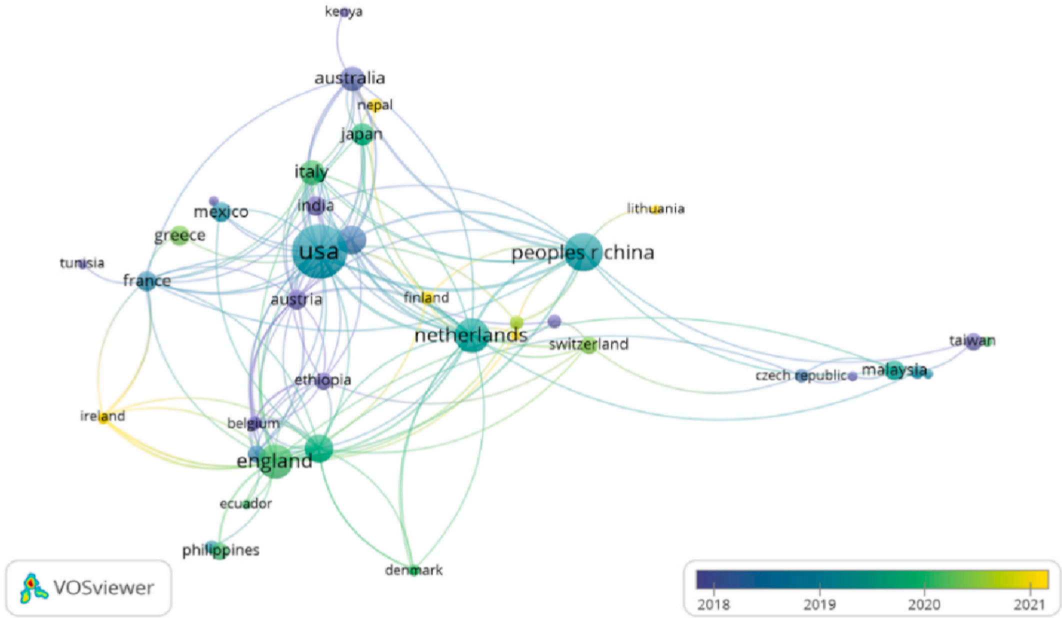

Fig. 3. Countries' co-authorship network in the WEF-Biodiversity nexus using VOS viewer.

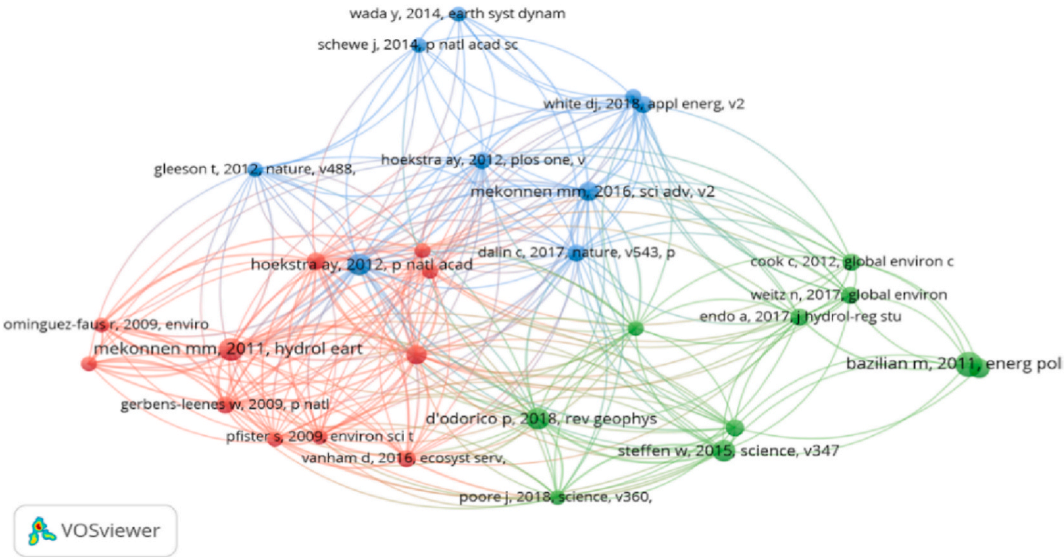

Fig. 4. Authors co-citation network based on cited references related to the WEF-Biodiversity nexus using VOS viewer.

approach would allow efforts to improve water use and food production sustainability, including water savings, improved irrigation efficiency, and more drought-resistant crop cultivation.

The prevalence of co-occurrence of keywords in the author's titles and abstracts that integrate the keyword analysis resulted in eight clusters (Fig. 5). In general, the red cluster forms the largest (15 keywords) and centralised research in WEF- Biodiversity nexus subject matter—and it is related to WEF nexus, environmental flows, and policy. The green cluster draws high attention to agriculture footprints and biodiversity conservation. Themes in blue clusters have drawn attention to agriculture land-use and the importance of addressing transitions at the landscape level. Blue sky centroids have attracted attention to sustainability transitions in agriculture through integrated assessment. Complementary, purple, brown, yellow, and orange, aggregations are related to multicriteria optimization through Geographical Information Systems (GIS), nexus thinking and forest, life-cycle assessment, and environmental impacts in agriculture.

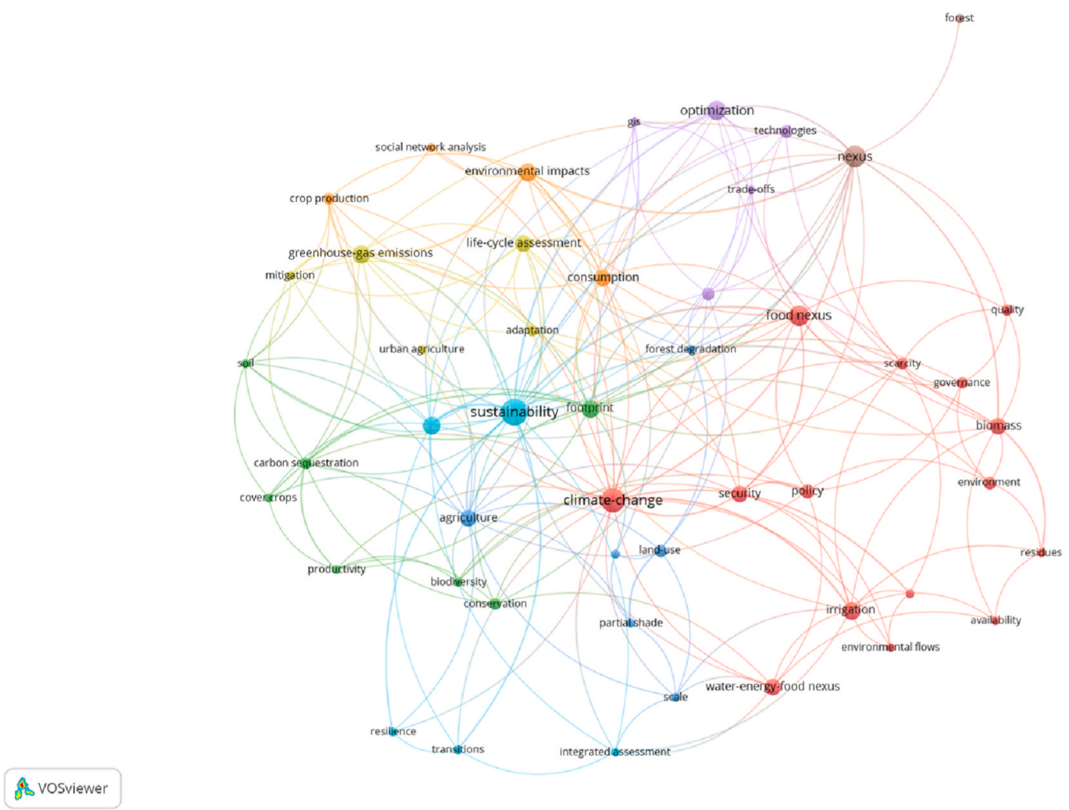

Fig. 5. Keyword co-occurrences network depicting the frequent occurrence of keywords visualised in the WEF-Biodiversity nexus using VOSviewer.

3.2. *Tree of science analysis*

Using complete records and references cited, we built a Tree of science (ToS) using currently available technological tools, such as an algorithm created for R that classifies items into roots, trunks, and leaves (80 papers prioritised: 10, 10, 60 papers respectively). As an additional result, word clouds (Fig. 6) were generated for the period 2009–2021, indicating the state and evolution of knowledge in the WEF nexus applied to biodiversity conservation. The search results yielded five document typologies distributed in 48 research articles, 21 review articles, 8 book and book chapters, 2 opinion articles, and 1 encyclopedia. These included a wide range of document types, e.g., research and review articles, chapter books, opinion articles, and encyclopaedias as shown in Table 1. Research and review articles were predominant with a significantly ($p < 0.05$) higher frequency (60 and 26%) in the review.

3.2.1. *Nexus assessment*

The nexus type, focus, and highlights varied significantly depending on the study. Generally, nexus types have considered the relationship between human groups, biodiversity, and WEF nexus at different relationship levels. For instance, Endo [48] identified four types of nexuses: water-food, water-energy, water-energy-food, and water-energy-food-climate change. They explored and described nexus regions, nexus keywords, and related stakeholders. Our findings related to the WEF nexus types, biodiversity conservation, and agri-food systems through the critical literature review are summarised in Table 2.

The scientific mapping of the WEF nexus efforts related to sustainable agriculture highlights and compiles expert views on policies covering different focuses such as planetary boundaries, livelihoods, co-production, and governance (Table 2). These applications

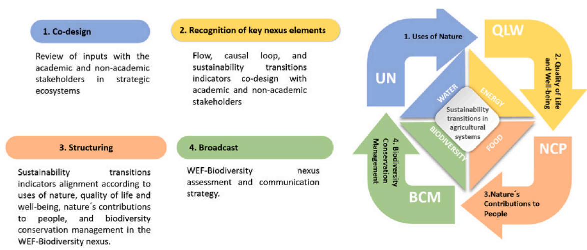

Fig. 6. Conceptual framework of the Water-Energy-Food-Biodiversity nexus.

Table 1
Summary of WEF nexus documents analysed in the review study.

Document type	Number of documents	% of the total	$p < 0.05$
Research article	48	60	0.00
Review article	21	26	0.00
Book or book chapter	8	10	0.00
Opinion article	2	3	0.02
Encyclopedia	1	1	0.01

Table 2
Classification of reviewed studies based on WEF nexus types and focus.

Nexus Type	Articles (n)	Focus	Highlights	References
Human-Nature	5	Planetary boundaries - resource security	Planetary boundary framework and the integrated approach to research development. Assessment of sustainability through human-nature interactions along the supply chain. Study of environmental pressures, human and ecosystems health, and landscape restoration actions.	[8,24,30–32]
Food-Water	2	Sustainability - value chain	A modelling framework for planning and decision-making on resources, ecosystems, and global biosphere management. Importance of Agri-food systems in food security, livelihoods, and human well-being. Analysis scenarios across all sectors and scales. Use of resources in agriculture and building capacity and incentives for effective governance.	[59,60]
Water-Energy	3	Resource security - sustainable agriculture	Direct and indirect boundaries applied in urban metabolism and multi-regional input-output model frameworks. Building-integrated scientific research tools. Measured trade-offs and synergies by dimension and region. Integrative policy management. Sectors transition scenarios. Optimal scenarios based on multi-criterion decision aid.	[61–63]
Energy-Water	3	Climate change - sustainable agriculture - land.	Integrated nexus framework based on modules and the role of technologies in achieving sustainable development. Strategies on climate, use, distribution, and productivity of the world's abandoned croplands and dependence on agricultural production systems. Addresses integrated assessment practices, application, and optimization of decision-making.	[64–66]
Water-Energy-Food	36	Planetary boundaries - sustainable agriculture - life cycle	Nexus scenarios simulation on drivers, synergies and trade-offs, adaptive capacity, and resilience dimensions in nexus practice with close links to human health and the environment. Governance models: innovative forms of cooperation and collaboration through co-production. Interdisciplinary and transdisciplinary domains of the nexus. Multi-criteria decision-making methods. Resource constraints and other local conditions, such as cultural practices and related ecosystem services.	[4,12,23,41,54,67–95]
Energy-Water-Food	3	Life-cycle - environment - resource security	Integrated nexus framework from political drivers, economic viability, and threat to resource supplies. Institutional capacity building in complex interactions.	[96–98]
Energy-Food-Water	3	Sustainable agriculture - governance - resource quality	Integrated nexus framework based on optimization-evaluation models. Biomass resources and human needs, and potential bioenergy crops. Assessment of sustainability, and environmental cost-benefits of crops. Roles, changes, and scenarios of sustainable agriculture and new biorefineries.	[18,99,100]
Food-Energy-Water	14	Planetary boundaries-SDG - sustainable agriculture - resilience	Integrated nexus framework. Analyses interactions between SDGs and planetary boundaries. Assesses risks and options for decision-making. Development of quantitative decision-making tools and cross-sectoral and stakeholder co-production. Analysis of factors that exacerbate and mitigate climate disruptions in the nexus, synergies, and trade-offs. Multi-target offset strategies. Integration of Ecosystem Services and soil into nexus analysis.	[33, 101–112]
Food-Water-Energy	2	Ecosystem - resource security	Integrated framework nexus approach and steps for a responsible agri-food system. Ecosystem services nexus from upstream-downstream linkages. Nexus requires increased cross-sectoral coherence and improved governance. Agri-food systems play a key role in the health and well-being of the human population worldwide.	[28,29]
Water-Food-Energy	10	Livelihoods - sustainable agriculture - co-production - governance	Integrated nexus framework and the intersectoral relationships in governance. It compiles expert views on sectoral policies covering different disciplines. Develop tools to improve productivity and sectoral policies, avoiding unintended consequences in other sectors. Multiple scenarios (socio-economic and climate change) as a prerequisite for developing sound adaptation policies and relevant action planning and co-production of models and indicators and interpretation of results with stakeholders.	[52,69,113–120]

developed tools to improve productivity and sectoral policies, avoiding unintended consequences in other sectors.

3.3. Thematic analysis

The thematic analysis in Table 3 provides a representation of the temporal evolution of WEF nexus research's critical themes related to biodiversity conservation and agri-food systems transitions during the 2009–2021 period in the Tree of science (ToS) analysis. Interestingly, the WEF nexus research has significantly expanded incorporating biodiversity conservation and its implications on agri-food systems' sustainable transitions.

4. Discussion: stressing out the importance of biodiversity conservation in the nexus

Here we examine the net outcome of treating the fourth area of the WEF nexus: biodiversity holistically. Complementary aspects that seem critical in Nexus thinking are land [87], and climate change [66]. Related to incorporating biodiversity in Nexus, approaches lean toward understanding biodiversity as a resource that provides essential functions for food provision [121–123] and considering ecosystem indicators that will facilitate addressing sustainability in the nexus [124]. When approaching ecosystems as a fourth pillar, solutions need to emerge within the supply chains of water, food, and energy as they affect ecosystems directly or indirectly [79]. However, some authors have suggested a more theoretical approach where biodiversity hotspots are vital to identify priority areas for conservation, nature restoration, and abandoned farmland [64], and are crucial to coproduce models of use and flow of resources in the water-energy-food-biodiversity nexus.

4.1. What goes on with the WEF-biodiversity conservation nexus?

4.1.1. Biodiversity conservation

Drivers in nexus thinking are related to the interrelationship between resources that determine scarcity, resource supply crisis, and failures in sectoral management strategies [91,124]. Improving sustainable resource use in the nexus requires identifying drivers and understanding synergies to guide sustainable resource management. Variation in drivers depends on geography, climate, economic development, social-political integration, and landscape transformation patterns analysis in a site-specific region [68]. Jarvie [125] argues that ecosystem services within the nexus are crucial pillars to support water, energy, and food security resources due to supply, regulation, and provision benefits linked to the kinetics of the nexus.

Even when the WEF nexus could attempt to incorporate other factors such as human capital and the influence of technological progress as well [87], driving forces are made up of different components that can affect social change or natural systems and should be carefully elucidated to understand the status, development, and management of resources, and to safeguard equity and sustainability [68]. The WEF-Biodiversity nexus assessment could put into context multiple connections that highlighted the main factors [68] responsible for resource degradation in the nexus, and alteration of nexus stability and food security [125]. In this sense, social aspects including population growth, poverty, lack of alternative livelihoods, economical aspects such as increased income variability, market shifts, institutional and policy change reviewing obsolete legislation, and climate change become highly relevant to understand drivers for change in the Nexus [68,125].

For instance, the numerous interconnections within the nexus represent the complex and inter-related nature of the coupled human-nature system, in which the development of hydropower is affected by climate change, investment plans, and technology innovation drivers having social, economic, and environmental impacts [89].

Research shows that the importance of water, energy, and food aspects varies when studying different nexus phenomena. For example, Zhao [61] indicates that when the economic system is an endowment by water resources, there are simultaneous trade-offs

Table 3
Temporal evolution and perspectives in WEF nexus research during 2009–2021 period.

Period	Main perspectives	References
2009–2013	At the onset WEF nexus research is related to resource security on the system and sustainable ecosystem management by analysing climate change and land use sceneries. Authors developed an integrated nexus framework with a focus on direct drivers of change framing the nexus from political motivators and modelling tools to support integrated decision-making.	[66,95,96,100]
2014–2017	This finding gradually shifts to include the analysis of Sustainable Development Goals and WEF-livelihoods nexus trade-offs, synergies, and external pressures and stressors at multiple spatial and institutional scales. In this sense, authors analysed how economic prosperity is reached at the cost of depleting forests and natural resources, all associated with rapid industrialization, high growth, domestic investment, improved water sources, and labour force participation. Thence, an integrated nexus framework based on modules and the role of technologies in achieving sustainable development strengthens strategies about climate change, and sustainable agriculture were decisive in the transition to the next period.	[65,94,99,112]
2018–2021	Embody use, distribution, and productivity of the world's abandoned croplands where agricultural production systems integrated assessment practices, and decision-making. Nexus scenarios simulation and hotspots on population, anthropogenic pressures, agrotechnology, drivers, synergies, and trade-offs. Adaptive capacity, and resilience dimensions in nexus practice related to human health and environment. Integration of Ecosystem Services and soil into nexus analysis were preponderant targets in this period.	[19,67,78,85, 105–109,115]

and synergies concerning economic development, social welfare, and environmental protection.

An essential element for human survival is the WEF nexus, the basis for a sustainable regional economy and the ecological environment [82]. Li and Ma [74] analysed Taiwan's WEF nexus with a life-cycle approach, estimating the three environmental impact categories from direct and indirect resource consumption such as climate change, human toxicity, and terrestrial ecotoxicity. A proposal to include ecosystems in the WFE nexus showed how the conservation of biodiversity and the sustainable use of ecosystem services are indispensable to achieving sectoral development goals successfully [116].

Worldwide scientific communities have engaged in finding WEF nexus strategic applications and implications to reduce biodiversity losses. For instance, Zhang [100] addressed the importance of the energy-food-water nexus considering future energy and food demand. However, besides this challenge Laspidou [77] identified that the decoupling of strong interlinkages among nexus sectors increased system resilience which implied a nexus chord plot that revealed strong resource interlinkages and nexus hotspots. In a similar line, Bakhshianlamouki [73] revealed critical interactions between agriculture practices and water availability in the context of a changing climate.

On the other hand, policy coherence has been identified as a driver for the measurement and articulation of nexus implementations [126], where the governance of the nexus plays a fundamental role in the innovation and diffusion processes while building political and institutional realities for the security of resources and equity and efficiency in their use [121].

Interestingly, research in European agricultural policy (Common Agricultural Policy- CAP) has shown that it is context dependent and often oriented towards political interests. In this sense, policy instruments and emerging analytical tools that incorporate statistics, behaviour and economic aspects apparently provide means to nourish emerging debates and needs, locating agriculture and agri-food systems right at the intersection between environment and climate interactions [127]. Additionally, the WEF-Biodiversity Nexus seems to be useful when understanding sustainability transitions in Agri-food systems. In this regard, research has explored the implications for agri-food systems, agriculture development and policymaking when considering changing contexts such as different rural configurations, digitalization, artificial intelligence, communication technologies, and broadening stakeholder involvement in the European Union [128] Therefore, WEF-Biodiversity Nexus research will require openness to understand how transitions occur at many different levels and sectors, and ultimately, interact with the way society manages resources and shapes agri-food systems.

Stakeholder participation in the governance of the nexus can promote mitigation trade-offs, synergies between resources, and environmental conservation in the context of Sustainable Development Goals [76] and Planetary Boundaries [32]. Our review shows that incorporating stakeholders and understanding decision-making processes is crucial for the nexus application. For instance, the term *"nexus crises"* is taken as an approach to practically explore and inform decision-making for climate impacts in the nexus. When examining climate shocks, other elements (such as infrastructure, healthcare, etc.) of the nexus interaction, reveal the vulnerable social relationships, which ultimately affect the capacity of response and social behaviour. In this sense, approaches of co-production, strategic thinking, collaboration, communication, the anticipation of societal responses, building up capacity, and bottom-up initiatives can aid to overcome these challenges. Addressing the linkages between policy-relevant requirements and transition scenarios is crucial in the process of knowledge co-production between scientists, resource managers [61], and the community.

However, it should be considered that power dynamics affect the co-production processes of water-energy-food nexus thinking, and so it's necessary to reveal the power tensions between actors to improve the decision-making processes [84].

In the case of the agri-food sector, a fundamental challenge is to adjudicate levels of the socio-ecological transitions that could clarify possible flows and trajectories. There is no doubt that some frameworks such as nexus thinking and "The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services" "IPBES" can pose some implications not only in the use of resources but also in the scenarios, scales, indicators, and long-term interactions that situate demands of biodiversity conservation which can be supplied or balanced by agri-food systems at micro-basin levels.

4.1.2. Biodiversity conservation and agricultural systems

Comprehending the WEF-Biodiversity nexus subject matter is essential for merging conceptual networks which depict key dimensions and elements to nexus assessment in agri-food systems.

Our results stress the urgency to evaluate the WEF-biodiversity nexus applied to socio-ecological transitions of agri-food systems through the analysis of nature, nature's benefits to people, good quality of life, and governance dimensions addressed by the IPBES framework [129,130]. This approach will lead to a more optimal allocation of resources [96], a reduction of biodiversity loss impacts, the diversification and enhancement of sustainable livelihoods, and the coherence of sectoral policies in tropical countries that optimise the Nexus interrelationships [129,130]. Identifying the interrelationships of a priori nexus dimensions integrates different territorial implications and closely related impacts which are vital to promote synergies and avoid potential tensions [96] and socio-environmental conflicts.

In terms of challenges, research has emphasised the importance of considering a more ecosystem-sensitive and stakeholder decision-making approach [112] when addressing nexus interactions, as well as in cases of transboundary river basins and inland fisheries [28,29,71,108,114,117] or when stressing the importance of water sources and its governance [31,61,63,83,120]. A growing number of research is proposing the need to incorporate governance aspects to address power dynamics and decision-making in the nexus [83,88,93]. For instance, Sušnik [87] concluded that under food scarcity scenarios, global malnutrition rates would increase, and therefore it is paramount to maintain, and potentially increase, yields, perhaps through intensification or by significantly reducing food waste.

Consistent with these considerations, resource management in agri-food systems in recent years faces the complex challenges of the increase in food production concomitant with the world's population growth rate. Accordingly, the rise in food production demands the intensive use of sustainable environmental resources with certain adverse effects [131,132] including biodiversity losses, high water consumption, land use change, a reduction in soil fertility, land fragmentation, and trade-offs that new automation technologies can create or shape.

When considering the implications for agri-food systems, our results showed the importance of analysing the demand, supply, and functional dynamics of agri-food systems. Agri-food systems and their cycle are vulnerable to significant ecological and environmental degradation and pollution, and biodiversity loss, which is extensively associated with the destruction of natural capital, such as forests, water, marine, and coastal resources, soil erosion and air pollution [97]. In a particular way, Li et al. [133] proposed a cooperative optimization model to manage water-land-food- energy nexus (WLFEN) and cope with climate change for agroforestry systems, evidencing the need for resource reallocation as they are sensitive to climate-change, and this would improve resource efficiency, economy, and environmental impact. To achieve tangible progress in response to nexus challenges, Heal [67] proposes that analysis of interactions should initially focus on nexus *"hot spots"* such as cities, semi-arid areas, and areas dependent on groundwater or meltwater threatened by climate change.

We highlight that the coordinated and sustainable development of nature, economy and society should safeguard ecosystem services - supply, regulation, habitat or support, and cultural functions such as nutrient cycling, bioturbation, enhanced plant growth, secondary seed dispersal, trophic regulation, and pollination [98]. This nexus analysis is essential for sustainable development and conceptually relevant to mitigate the risk of unintended consequences of large-scale sectoral investments and negative trade-offs. For instance, Lal [111] considered that ecological benefits (positive footprint) of ecosystem services in the nexus should be assessed by decision support tools that quantify synergies and trade-offs. Co-production of food security adaptation plans, with the critical involvement of local communities, is key for biodiversity conservation. On the other hand, Wichelns [92] states it is vital in the nexus analysis to integrate relevant interactions to agriculture in tropical countries from dimensions such as people, soil, land tenure, labour, plant (phosphorus) nutrients and seeds, livelihoods [134], artisanal and inland fisheries [60], financial credit, and advice from extension services.

Prospects encompass the need to consider within the framework of systems modelling, different socio-economic scenarios complementary to a representative range of climate change scenarios so that uncertainty and consequences of global change are reflected, and robust adaptation policies and relevant action plans can be developed as pointed out by Momblanch [115].

For instance, in our review, we identified that sustainability transitions should be addressed by optimal scenarios based on multi-criteria decision-making analysis (MCDA) which integrates economic, social, and environmental performance that can facilitate the design of future policies for regulating resources and transitions [61]. In this way, assessing the nexus at different scales of analysis will contribute to the understanding of the complexity of the nexus and the pros and cons in its various dimensions [78]. In this context, Giampietro [135] posits that in the same way as organisms, social-ecological systems (and their components) must metabolise material and energetic inputs to survive and evolve, thus producing useful products and residues.

In the same line, the resource nexus assessment as a complex problem has been proposed by Serrano-Tovar [78]. This assessment integrates the depiction of socio-ecological systems performance through the elements of flow and metabolic reserve (crop production) and their characteristics (area and workers) along the dimensions and scales of analysis. Therefore, the WEF-Biodiversity nexus approach will require a scenario analysis approach that allows the comprehension of how sustainability transition levels could be reached. Strengthening the different knowledge networks through a co-creation roadmap would contribute to the generation of public policy in scenarios of transitions towards sustainability in agri-food systems.

4.2. Are sustainability transitions in agricultural systems essential to address the water-energy-food-biodiversity conservation nexus?

As shown in our results section, the analysis of key themes presents the knowledge gaps that can support the WEF-Biodiversity nexus assessment and the practical application of agri-food systems' socio-ecological transitions. The WEF nexus [13] and the socio-economic metabolism [136] thinking are considered promising solutions for Agri-food systems and resource sustainability. While socio-economic metabolism aims to self-replicate and evolve the biophysical structures of human society, the nexus approach provides a useful interdisciplinary analysis of sustainable society-nature interactions by highlighting relations between different resources [13,136]. Nexus approaches have been evolving with restricted academic work, primarily with the intention to analyse the WEF-biodiversity nexus and recently, centring in the sustainability transitions of agri-food systems.

It is well known that water, energy, food, and biodiversity conservation play a key role in sustainable transitions of the agri-food systems. This implies enhancing ecological efficiency at use and access to natural resources by reducing detrimental impacts on the environment and improving support, regulation, and cultural ecosystem services provision [137]. The emphasis on the descriptions of WEF- nexus literature without mentioning the possible interlinks with biodiversity in the sustainability transitions analysis of agri-food systems, compels a narrowed vision of management in sustainable-use protected areas, landscape restoration actions [24], and elements of agroecology [27].

Nonetheless, the potential contributions toward the effective management of biodiversity conservation continue to gain much attention. Considerable research [138–140] is available to analyse the biodiversity element in the interrelationships with nutrition [138] bio-culture [138,140], and the WEF nexus [139].

Consequently, we stress out that biodiversity can better be conserved and enhanced as part of traditional agricultural and food systems due to knowledge of biodiversity and the use of food culture to promote positive behaviours [138]. In this line, Argumedo [140] argues that a key to harmonising nutrition, resilience, and adaptive capacity is the biocultural diversity of indigenous and traditional peoples, who collectively maintain longer human experiences with food provision under environmental change. This condition allows them to support a diverse range of domesticated species, gather wild foods to supplement their diets and livelihoods and regional stocks in developing countries.

In the case of South Global, Spring [139] pointed out that the nexus between WEF-Biodiversity and security could be improved in Mexico despite climate change and organised crime through a shift that enhances human and environmental security by transitioning to policies oriented towards sustainable development. This research reflects the global problems related to the climate system, water, biodiversity, soil deterioration, and the usefulness of a human security approach to help rethink the linkages in the water-energy-food-biodiversity nexus and overcome the hidden military and political implications of security.

Similarly, an analysis in Colombia defined the biodiversity management processes which are appropriated and managed by social actors to modify the trajectories of undesired change in the ecological and social system. This research would lead to concerted actions toward the optimization of the well-being of the population and the environmental security of the territory [141]. In this case, the study related socio-ecological transitions to technological proposals linked to nature-based solutions.

Strategically research spotlights the co-production and prioritisation of questions according to global megatrends such as the nexus, and the key role of the nexus in the protection of cultural and social values [142]. These scientific contributions pointed out the key knowledge gaps around developing or adapting methodological tools to facilitate co-creation processes through participatory and action-oriented approaches, and the overall strategy to enhance the efficiency and resilience of agri-food systems consists of diversification efforts toward building synergies strengthening recycling, and minimising trade-offs [27]. As a key research opportunity, this exploration elucidated the incorporation and protection of cultural and social values to empower citizens, especially indigenous peoples.

More recent contributions in sustainability transitions associated with the application of the nexus in sustainability transitions emphasise on the evolution and changes in resource use, synergies, and tensions applied to innovation processes [142]. Another research proposal suggests nature-based solutions addressing the water-energy-food nexus applied to urban environments [143]. In addition, studies are concerned about the development of digitalization and Big Data tools to achieve the SDGs in the nexus, and the social metabolism water-energy-food nexus in agricultural watersheds [19,144].

These contributions essentially reveal knowledge gaps in agricultural and food systems which included a better understanding in terms of spatial and temporal scale dynamics, including feedback mechanisms to maximise synergies and complementarities and minimise trade-offs. In this sense, it is mandatory to develop multidimensional frameworks and assessment tools to elucidate the status of sustainability transitions in areas where agri-food systems are located.

Our review allowed us to localise the principal research gap on the WEF nexus. The gap implies that the trajectory of the use and flow of nature's benefits to people at the WEF-Biodiversity nexus in the context of agri-food systems, have yet to be elucidated, and scenarios of socio-ecological transitions to sustainability that incorporate biodiversity conservation must be realised. This knowledge gap suggests the analysis of the direct causes and effects where human activities - agri-food systems threaten biodiversity and global and local culture [3,4]. On the other hand, elucidating socio-ecological transitions towards sustainability in agri-food systems will have a direct effect on the development of policies on sustainable transitions in agri-food systems related to biodiversity conservation.

As a precondition to solving the gaps found in this review, a new methodological approach in the WEF-Biodiversity nexus research could address the synergies and challenges of each element applied to sustainability transitions.

4.2.1. WEF-biodiversity nexus approach

While previous research has focused on the role of technologies in achieving sustainable development, these results harmonize technical and biodiversity management perspectives on the interrelationships between Water-Energy-Food-Biodiversity nexus. These results should be considered when restoration of ecological functions is required through productive reconversion exercises and sustainable agricultural production at the landscape scale. It is essential to mention the need for staggered researchers aimed at decision support in the resources and biodiversity management and development of sustainable agriculture transitions involving appropriate socio-ecological characteristics.

Furthermore, agriculture production systems perform distinctive shapes and interrelations with biodiversity. The so-called *transition* to more sustainable agriculture plus the similar complexity character implies the interrelations with secure nature's contributions to people, codesign process, and promising response options of nature conservation and management. This complexity responds to the demand to understand the dynamics of the interrelated dimensions of the WEF-Biodiversity nexus. In this context, we propose a practical scheme adopting a System Dynamics Modeling (SDM) approach that would allow establishing scenario analysis of how agricultural systems should make transitions toward sustainability at the landscape level. The WEF-Biodiversity methodological framework aims to address the gaps identified in the WEF nexus by integrating both WEF and Biodiversity elements into the same framework to address the synergies and challenges in sustainability transitions of agricultural systems at the landscape level.

The WEF-Biodiversity nexus comprises complex interactions between diverse sustainable agricultural systems transitions at various scales, influencing and being influenced by dimensions such as uses of nature, quality of life and well-being, nature's contributions to people, and biodiversity conservation management in each element of the nexus. In the framework we hypothesise that an integrated nexus framework can be operationalized in a co-production roadmap to improve biodiversity conservation and sustainable agriculture policies. The interlinkage level proposed in this framework is WEF nexus within Biodiversity conservation and management. Remarkably, different biodiversity ecosystems can have different contributions to sustainable transitions and to develop sustainable WEF nexus (Fig. 6).

5. Conclusions gaps and insights for future research

We conclude that Nexus research has transited from an understanding and conceptualization phase to an operationalization and implementation phase, and with time, practicality, and inclusion of other social and political aspects have gained relevance. Our review critically situates the nexus types, focus, and highlights regarding biodiversity and its relationship with sustainability transitions in the WEF-Biodiversity nexus where Sustainable Development Goals (SDGs) and the Planetary Boundaries seem to facilitate the dialogue between the IPBES proposal and Nexus assessment. In this sense, emerging debates, and needs, locating agriculture and agri-food systems right at the intersection between environment and climate interactions should derive in powerful policy instruments and analytical tools to elucidate the WEF-Biodiversity nexus.

Our research has determined the knowledge gaps, challenges, opportunities, and prospects of the WEF nexus in Biodiversity conservation related to agri-food systems. This systematic review revealed that the WEF- Biodiversity nexus has great importance in the agri-food systems' socio-ecological transitions and biodiversity conservation policies. Additionally, the WEF-Biodiversity Nexus seems to be useful when understanding sustainability transitions in Agri-food systems. In this regard, WEF-Biodiversity nexus research will require openness to understand how transitions occur at many different levels and sectors, and ultimately, interact with the way society manages resources and shapes agri-food systems, considering changing contexts and the implications for sustainability transitions in agriculture systems in policymaking.

Therefore, our paper highlights the value of nexus thinking in Water-Energy-Food-Biodiversity interrelationships and the usefulness of driver analysis, and trade-offs. We emphasise that complex challenges of the long-term sustainability of resource management in agri-food systems require a holistic, transdisciplinary, and multi-stakeholder co-production routing sheet to elucidate resource flow and use. The results confirmed that nexus approaches have been evolving within restricted academic work. Thus, the nexus framework applied to sustainability transitions in agri-food systems related to biodiversity conservation is still incipient, therefore, necessary. As discussed above, the co-creation process, the use of a broader framework of indicators of transitions to sustainability, and the inclusion of the dimensions of multi-criteria analysis and IPBES would help to broaden the debate on the nexus, incorporate the concept into policies, determine the status of socio-ecological transitions in areas of sustainable use, and evaluate how to adopt nature-based solutions. Addressing the complicated nexus challenges is essential to establishing a co-creation process roadmap when engaging with stakeholders.

Author contribution statement

Diana C. Moreno V: Conceived and designed the experiments; Per- formed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Carolina del Pilar Quiñones H: Conceived and designed the experiments; Per- formed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Olga L. Hernández Manrique: Conceived and designed the experiments; Per- formed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

No data was used for the research described in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17016.

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