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Ten Years of Research on the Water-Energy-Food Nexus: An Analysis of Topics Evolution

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This study explores how the concept and research on the water-energy-food (WEF) nexus has evolved over time. The research uncovers the key terms underpinning the phenomenon, maps the interlinkages between WEF nexus topics, and provides an overview of the evolution of the concept of WEF nexus. We analyzed published academic literature from the Scopus database and performed both qualitative and quantitative analyses using Natural Language Processing method. The findings suggest that the nexus approach is increasingly evolving into an integrative concept, and has been incorporating new topics over time, resulting in different methods for WEF nexus research, with a focus on interdisciplinary and inter-sectoral analyses. Through the five periods outlined, we have identified the nexus approach debate focused on the following predominant topics: i) Trend 1 (2012–2016) debates on WEF nexus for water management and natural resource security, ii) Trend 2 (2017–2018) linkages between the nexus, the sustainable development goals and green economy, iii) Trend 3 (2019) WEF nexus governance and policy integration, iv) Trend 4 (2020) application of the nexus concept on different scales, including regions, countries, watersheds, urban areas as well as other components coupled to the WEF nexus, and, v) Trend 5 (2021) climate change and urban nexus challenges.

Keywords: water-energy-food nexus, WEF nexus, WEF nexus governance, policy integration, topic modeling analysis

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INTRODUCTION

The water-energy-food (WEF) nexus approach proposes integration and interdependence across various sectors as a fundamental step for ensuring resource security in the global context of climate crisis, resource scarcity, and increasing and competing demands for water, energy, and food (Hoff, 2011; World Economic Forum, 2011; FAO, 2014; IRENA, 2015). It has been endorsed as a valuable tool for quantifying and assessing the relationships between sectors as well as for interpreting complex political agendas to better inform policies, government programs, and sectoral planning. This, in turn can help address the challenges of achieving integrative governance,

provide institutional incentives, and establish norms for intersectoral cooperation (Bizikova et al., 2013; Flammini et al., 2014; Lazaro et al., 2021a). The logic behind the WEF nexus is that it shifts attention from a one-sector view to a more integrated one (Bazilian et al., 2011; Al-Saidi and Elagib, 2017; Zarei, 2020). Overall, there is no energy production without water, no water supply without energy, and no food production without these key resources. Therefore, the WEF systems are fully intertwined and interdependent. Impacts on one resource, whether from the demand or supply side, affect all others and thereby, the entire production or consumption chain.

Debates and concerns about water and food crises, the perspectives of climate change, and the volatility of food and energy prices in the late 2000s brought about the emergence of the nexus approach as a way of framing cross-sector and cross-scale interactions (World Economic Forum, 2011; Allouche et al., 2015; Middleton et al., 2015). Studies have shown growing links between food, energy, and water availability. Food and energy prices are significant risk factors that affect water stock prices, and water is a limiting factor that control food production and energy generation (Tadesse et al., 2014; Vandone et al., 2018). Competition in water use for food and energy production has been at the core of an emerging debate about the WEF nexus, as the growing urban population demands more food and energy, as well as water from limited freshwater resources, which in the context of climatic variability will be increasingly scarce (Hoff, 2011; D'Odorico et al., 2018). This relationship within the WEF nexus sectors was evident during the World Economic Forum in 2008 when prominent business leaders issued a "call to action" on the ways in which resource security across a WEF nexus and climate is linked to economic growth (World Economic Forum, 2011).

However, as stated in the studies by Dahlmann and Bullock (2020) and Lazaro et al. (2021b), despite the WEF nexus initial conception has emerged within the prominent business leader at the World Economic Forum, little is known about the extent to which businesses practice nexus thinking. The nexus research agenda has drawn increasing attention since the 2011 Bonn conference "*The Water, Energy and Food Security Nexus—Solutions for the Green Economy,*" and it has being used to express an "integrative imaginary" (Cairns and Krzywoszynska, 2016). This milestone event highlighted the need to understand the nexus approach to develop policies, strategies, and investments to maximize synergies and mitigate trade-offs, thus improving governance across nexus sectors through active participation among government agencies, the private sector, academia, and civil society (Hoff, 2011).

The final report of the Bonn conference emphasized the current status of the debate and reported on the challenge that humanity would face if nothing was done to improve water management in the coming decades (World Economic Forum, 2011). The results of this conference served as a contribution to the United Nations Conference on Sustainable Development "Rio+20," held in 2012, which in its final document, "The future we want" called for the adoption of "holistic and integrative approaches to sustainable development" (paragraph 40); it also adopted "the promotion of integrated approaches to planning and building sustainable cities and urban settlements, including supporting local authorities, raising public awareness and increasing social participation in decision-making" (paragraph 135) (United Nations, 2012). In 2015, the text of the UN Agenda 2030 adopted this so-called "integrative approach" as a guiding principle, through which the existing connections between social progress, economic growth and environmental protection may be promoted (United Nations, 2015). This demonstrates that nexus thinking and resource management are imperative for the achieving the United Nations Sustainable Development Goals (SDGs).

Furthermore, other international organizations, such as the Food and Agriculture Organization of the United Nations (FAO) have indicated that the WEF nexus approach can ensure food security and achieve sustainable agricultural development (FAO, 2014; Bervoets et al., 2018). The International Renewable Energy Agency (IRENA) emphasized that renewable energy technologies could address some of the trade-offs between water, energy, and food, bringing substantial benefits to all three sectors. Furthermore, renewables can reduce competition by providing energy services using less resource-intensive processes and technologies (IRENA, 2015). However, technology is not a simple solution to the complexity of the WEF nexus because its successful diffusion depends on institutional structures, regulation, and political processes (Hoolohan et al., 2019; Lazaro et al., 2021a). It also depends on incentives and tax reforms and on the achievement of multi-sectoral benefits and transformation of the existing silo studies of innovation, as its processes and structures are questioned within three major resource sectors (Hoolohan et al., 2019).

Some researchers argue that nexus debates mask a bigger discussion on resource inequality and access, with a tendency toward managerial security framing technical debates, hiding its politics, and ignoring deep inequalities (Allouche et al., 2015; Wiegleb and Bruns, 2018). For these authors, since the nexus concept was introduced by business leaders at the World Economic Forum, it been appropriated into powerful managerial discourses in natural resource debates framing business imperatives and global neoliberal policies (Allouche et al., 2015; Leese and Meisch, 2015; Middleton et al., 2015). This is aligned with environmental discourses that propose market-based solutions (Dryzek, 2013) and neoliberal governmentality (D'Odorico et al., 2018; Rodríguez-de-Francisco et al., 2019). These critical studies mainly emphasize that the socio-political aspects of the nexus concept of resource use and allocation were overlooked and point out that the prevailing technical-managerial nexus framing is inadequate for addressing social aspects such as poverty alleviation and reduction of inequalities, energy justice, water and food justice, and power imbalances in resource governance (Allouche et al., 2015; Wiegleb and Bruns, 2018; Giatti et al., 2019).

Despite the growing literature on the WEF nexus, there are still gaps on the application of nexus frameworks for policy recommendations (Gain et al., 2015; Pahl-Wostl et al., 2018; Silalertruksa and Gheewala, 2018; Olawuyi, 2020). This calls for further analyses of the interactions between decision makers that aim to seek and achieve common

and equitable decisions, highlighting that the governance and policy integration dimension for the WEF nexus is as important as physical analyses (Bazilian et al., 2011). Furthermore, the literature on the WEF nexus emphasizes the need for interdisciplinary research efforts to link knowledge and search for cross-sector dynamics and improvements in policy coherence to tackle the imminent challenges of our times (Foran, 2015; Howarth and Monasterolo, 2016; Wichelns, 2017). However, some authors are concerned that science also lacks a consensus on which approach to the WEF nexus is most appropriate (Newell et al., 2019; Simpson and Jewitt, 2019), and understanding how nexus topics have evolved over time can help in the development of frameworks, methods, and policies aimed at integrating WEF resources.

The WEF approach follows the traditions of attacking complex multidimensional policy issues through the connection among different systems, which are often dealt with without much integration (Weitz et al., 2017; Pahl-Wostl, 2019). However, WEF is more about the trade-offs that exist among the three elements. Integration among WEF systems could reduce some of these trade-offs. The WEF nexus is different from the past applications of the system approach, which focused on solving problems in a specific sector, such as Integrated Natural Resources Management (INRM) and Integrated Water Resources Management (IWRM). Thus, the improvement in the effectiveness and efficiency of a policy for tackling complex problems, such as climate change, is less on deploying resources in a specific sector or creating a new sector and more on the integration among different sectors. As described by Lazaro et al. (2021b, p. 9) "The nexus approach is seen as a transformative and shifting paradigm from the traditional 'silo' thinking approach, to a new model of doing business and decision-making wherein policy integration for resource management processes can increase the efficiency of natural resource use."

In this study, we identify the key topics driving the evolution of the nexus concept over time. We seek to bring together the key terms underpinning the phenomenon to build a map of the interlinkages between WEF topics in the literature based on the following key questions: i) What research exists to date on the WEF nexus? ii) How have WEF nexus topics evolved in the last ten years? and, iii) What are the promising approaches and research gaps in the WEF nexus literature? To answer these questions, we conducted a topic modeling analysis through supervised latent Dirichlet allocation (sLDA) method to assess the nexus literature in the Scopus database. The aim of this article is to present details on how the nexus concept and framework have evolved over the last 10 years, highlighting recent trends in concept application. Based on our findings, we also discuss why the nexus approach for governing WEF at the urban scale has received increasing attention in the literature to date, despite underlying assumptions about interdependencies among WEF systems that ultimately affect WEF availability and securities. Finally, we highlight some governance and policy implementation challenges in the development of frameworks for the WEF nexus.

MATERIALS AND METHODS

The analysis was divided into four steps. First, we collected published scientific articles on the WEF nexus. These articles were then analyzed using the bibliometrix, R-package to create thematic dictionaries of the topic's trends. In stage three, we performed a supervised topic modeling analysis and examined the existing topics in the different groups. Finally, through a qualitative analysis and by extracting the elemental context, we identified the predominant discourses on selected topics from the data.

To identify published articles, we used the Scopus database with the keyword "water-energy-food nexus" with no timeframe restrictions. We found a total of 681 articles up to December 31, 2021, as shown in **Figure 1**; since 2012, the number of public articles has been increasing. We then created a corpus with the abstracts of all these published articles, and proceeded with the bibliometric analysis using the bibliometrix software (Aria and Cuccurullo, 2021) to generate the thematic trends. These thematic trends are associated with their respective keywords, which were used in the construction of dictionaries, and each topic with its respective keywords is associated with the dictionary. We obtained a set of thematic dictionaries for each period. Some topics were repeated in several periods, while others were split into other themes. We performed the analysis for five periods: 2012–2016, 2017–2018, 2019, 2020, and 2021, each period independently, trying to be equitable in the number of articles for each period.

From the thematic trends, we performed the supervised latent Dirichlet allocation (sLDA) to model and structure the topics. A graphical representation of the model's workflow is show in **Figure 2**, where nodes are random variables, edges indicate a possible dependence, shaded nodes are observed variables, and unshaded nodes are hidden variables (Blei and McAuliffe, 2009). LDA topic modeling "is a generative probabilistic model of a corpus. The basic idea is that documents are represented as random mixtures over latent topics, where each topic is characterized by a distribution over words" (Blei et al., 2003, p. 996). In supervised sLDA, a response variable connected to each document is added to the LDA. In the sLDA model, users know a priori what they wish to show. For example, if the goal is to forecast a store's revenue from different inputs (day of the week, advertising, and promotion), then the model will be trained with historical data to forecast future revenues. In this study, we know a priori the topics trends from the previous bibliometric analysis. The sLDA allows to model both, the documents and responses, in order to find latent topics that will best predict the response variables for future unlabeled documents; it enables the description of themes by means of the probability of their characteristic words, either specific or shared by two or more themes (Blei and McAuliffe, 2009).

In this study we used the T-Lab's topic modeling of the emerging themes tool, which analyzes word co-occurrences through probabilistic modeling, from which the following operations were carried out: exploring the characteristics of each theme; the relationships between the various themes; assessing the semantic coherence of each theme; testing the model, and

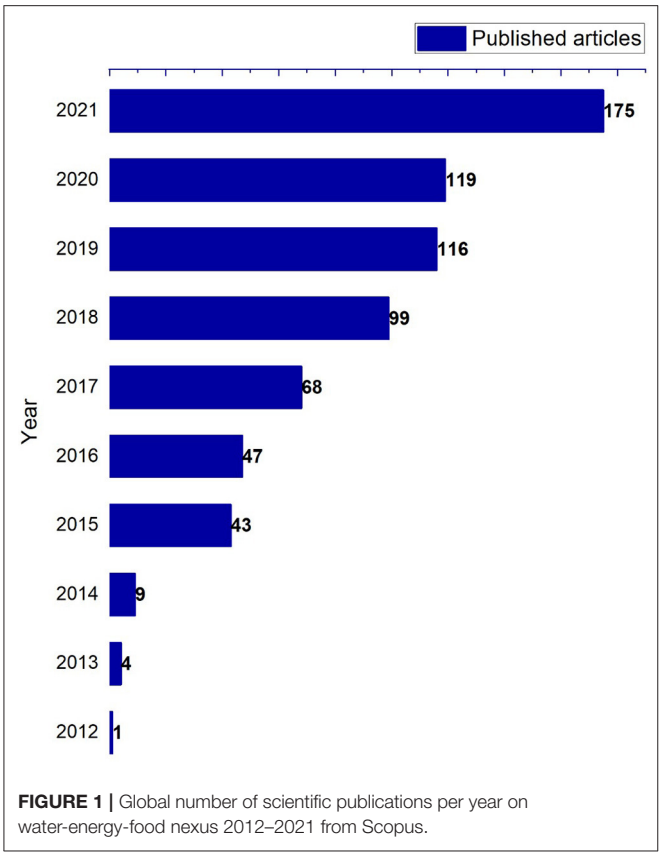

FIGURE 1 | Global number of scientific publications per year on water-energy-food nexus 2012–2021 from Scopus.

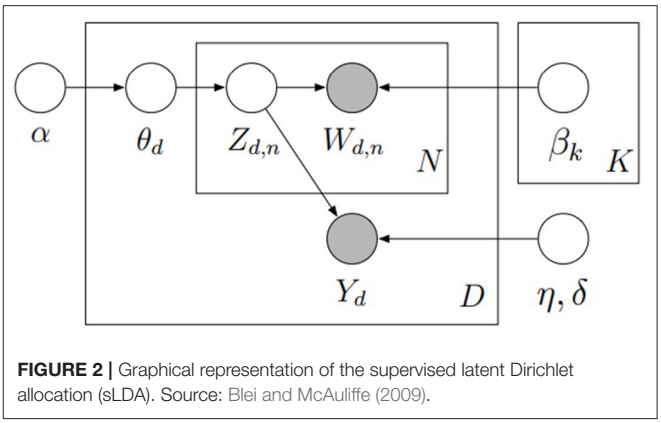

FIGURE 2 | Graphical representation of the supervised latent Dirichlet allocation (sLDA). Source: Blei and McAuliffe (2009).

applying the model by creating a new thematic variable, the values of which are the chosen topics. We also exported a dictionary of categories, which was used for analyses using another tool (Lancia, 2021). To visualize the results, we used a Multidimensional Scaling (MDS) map for each trend. MDS permits the analysis of similarity matrices to provide a visual representation of the relationships among data within a space of reduced dimensions (Lancia, 2020).

Furthermore, as proposed by Benites-Lazaro et al. (2018) we combined sLDA with qualitative analysis by the means of extracting the "elemental context," which consists in the extraction of the discourses from published articles to certain topics. The elemental context fosters the development of insights into how "texts and talks" are addressed, and in this study, it shows how every published article addresses the WEF nexus, allowing for qualitative analysis.

RESULTS AND DISCUSSION

We found that the most predominant topics in the WEF nexus research were divided into five periods, i.e., 2012–2016, 2017–2018, 2019, 2020, and 2021 (**Figure 3**). In the first period (2012–2016) the main focus was on water-related issues, and water was considered as a cross-cutting issue in the nexus, which should be linked to governance changes in other sectors (Al-Saidi and Elagib, 2017). The water-related focus can be linked to our previous understanding of the role of virtual water and water footprint with respect to showing global connections between water resource scarcity and demands for food production (Allan, 2011). This "water centrism" (Urbinatti et al., 2020) can also be the reflex and legacy of both: first the resource scarcity crisis and second the holistic, systemic and integrated water governance approach proposed by the IWRM.

In the early 1990s, the IWRM systemic and integrated water governance approach was "rediscovered" by some water experts, and the concept was heavily promoted by specialists and international institutions as a mantra for integrated water resource management to solve water problems (Biswas, 2008). IWRM was considered as a "process to promote the coordinated development and management of water, land and related resources to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment" (Global Water Partnership, 2011). However, the criticism of this approach is related to its water-centrism, based on the fact that the IWRM focuses more on the role of water resources as having important connections to other sectors (Grigg, 2019). In addition, water management principles have triggered changes related to policies, laws, and institutions in many countries. However, water sector reforms have not, been an all-round success nor have they halted the water crisis (Benson et al., 2015; Al-Saidi, 2017). Criticism of the IWRM approach has been reiterated with the emergence of recent proposals for integrated management paradigms, such as the WEF nexus.

One of the criticisms addressed at the WEF nexus was based on IWRM's previous experience of not having improved integrated governance (Wichelns, 2017; Grigg, 2019; Roidt and Avellán, 2019). However, some differences between the two approaches are described by Benson et al. (2015). First, while IWRM is water-centric, which attempts to engage other sectors from a water management perspective based on a river-basin scale, the WEF nexus approach highlights multi-centric and multi-scales, and treats different sectors as equally important as its departure point. Second, with respect to governance, the nexus conceptualizations provide few normative principles, while the IWRM forwards "good governance" principles such as transparency, collaborative decision-making and the use of

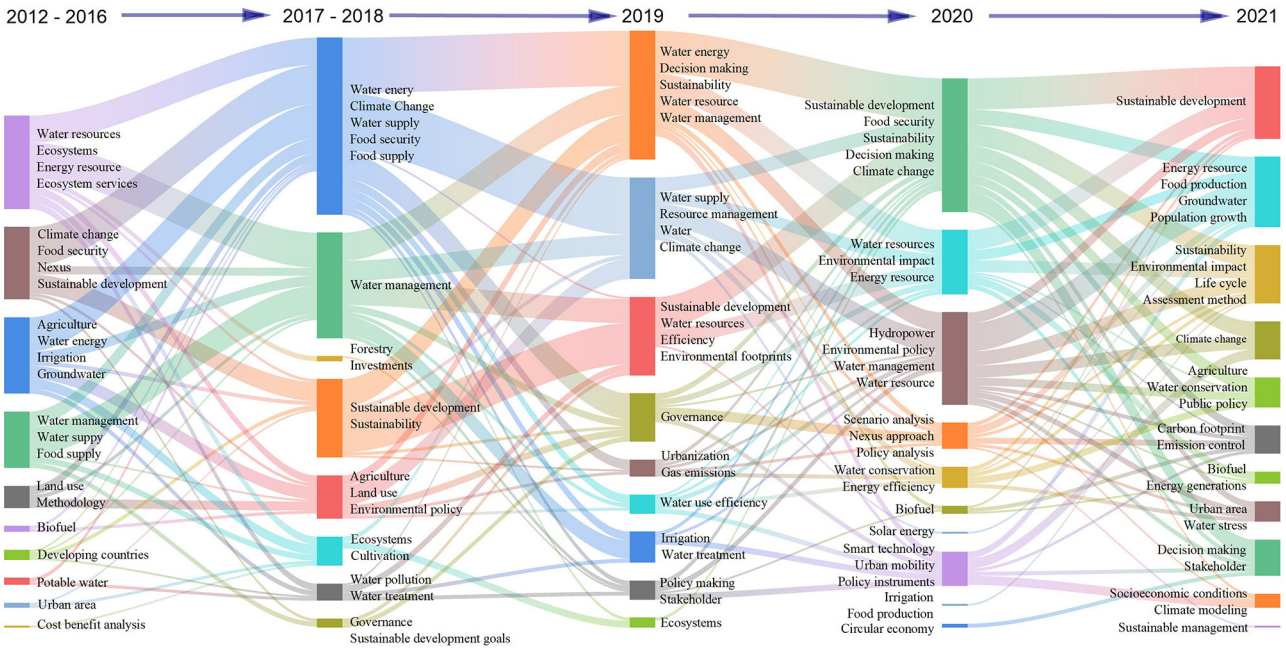

FIGURE 3 | Sankey diagram of the thematic evolution on the WEF nexus research (2012–2021).

specific policy instruments with equity and sustainability (Allan and Rieu-Clarke, 2010; Benson et al., 2015).

The crisis and risk of resource scarcity was the predominant discourse in the 2011 World Economic Forum report, which outlined several interrelated global risks from increasing volatility in food prices, climate, water, and energy, but mainly the security risk of fresh water. Water security was argued by this organization to be at the heart of social, economic, and political issues, and as at gossamer that links the web of food, energy, climate, economic growth, and human security challenges that the world economy will face over the next few decades (World Economic Forum, 2011). Given the resource scarcity risk, the World Economic Forum first proposed the concept of the nexus in 2008. The following year, in 2009, the erstwhile UN Secretary-General Ban Ki-Moon underlined the need to deal with the resource scarcity crises at the World Economic Forum meeting in Davos. Companies such as Coca-Cola and SABMiller have released documents depicting water stewardship strategies and programs to address water scarcity and shared resource risks (Lazaro et al., 2021b). This risk of resources scarcity was named as a "perfect storm" by John Beddington, to whom these dramatic problems with water, food, and energy are intimately connected, therefore we cannot think of dealing with one without taking the others into account (Sample, 2009).

Emerging studies on the nexus approach suggest that understanding the links in the WEF nexus in the context of climate change is important to avoid future conflict and how political and social stability are significantly correlated with food-water-energy security (Gain et al., 2015; Abbott et al., 2017; Zarei, 2020). Water scarcity and food and energy crises with social unrest could destabilize political systems, both within individual countries and beyond national borders. The global spike in food prices in 2008 and 2010–2011 provides evidence of the potential impact of food insecurity on conflict (Abbott et al., 2017). For example, studies have pointed out that climate variability, such as less rainfall and warmer temperatures was a contributing factor to the Arab Spring when prolonged drought in 2011 affected food production, sparking the mass migration of rural workers into Syrian region (Johnstone and Mazo, 2011; Bleischwitz et al., 2014; De Châtel, 2014). The report of the World Economic Forum emphasized that water shortages escalate food insecurity, disrupt energy, constrict trade, create refugee crises, and undermine authorities (World Economic Forum, 2011). It can also intensify conflicts by driving rural-urban migration (Abbott et al., 2017), and international migration, exacerbating international tensions, as water is increasingly used as a geopolitical instrument (World Economic Forum, 2022).

In fact, as **Figure 3** shows, the WEF nexus debate was driven by water-centrism and other dominant topics such as sustainable development, climate change, resource governance, water-energy, water-food or energy-food, and different research scales, including watersheds, cities, and urban areas, as well as methods and models, such as the WEF nexus tool 2.0 (Daher and Mohtar, 2015), hybrid input-output (IO) frameworks (Bellezoni et al., 2018; Tabatabaie and Murthy, 2021; Vats et al., 2021), life cycle assessment (LCA) (Mannan et al., 2018; Batlle-Bayer et al., 2020; Li and wen Ma, 2020), qualitative models (Lazaro et al., 2021a), system dynamics modeling (Tan and Yap, 2019; Sušnik et al., 2021), network analysis (Kurian et al., 2018; Benites-Lazaro et al., 2021), coordinated coupling model (Han et al.,

2020; Liu et al., 2020), agent-based model (Haltas et al., 2017; Bazzana et al., 2020; Falconer et al., 2020), Institutional Analysis and Development (IAD) (Villamayor-Tomas et al., 2015), topic modeling (Benites-Lazaro et al., 2018), and Bayesian network method (Chai et al., 2020; Shi et al., 2020; Wang et al., 2021).

Moreover, there are studies that go beyond the three water-energy-food nexus components and include land, policy, governance, labor, and innovation as influencing factors within the nexus (Lazaro et al., 2021a), as well as water–food–labor nexus (Distefano et al., 2022) and waste-WEF nexus (Abdel-Aal et al., 2020; Falconer et al., 2020; Udugama et al., 2020). Nevertheless, studies on different arrangements among other intertwined sectors also maintain similarities in terms of searching for synergies and mitigating trade-offs, which contribute to nexus thinking.

To provide the reader with an overview of the evolution of WEF nexus topics over time, we present below the five trends found by our analysis, followed by discussions on the main topics related to the WEF nexus in different periods between 2012 to 2021.

Trend 1 (2012–2016): The Nexus in Water Management and Natural Resource Security

We found in trend 1 that the predominant topic on WEF nexus research was related to water issues and security in natural resource use. **Figure 4** shows the topics with the highest frequencies in data analysis. The analysis is divided into four quadrants with thematic clusters. For example, the topics of biofuel, renewable energy, and cost-benefit analysis are shown in yellow. In green cluster topics on water-related issues linked to agriculture and irrigation predominate. Food security, climate change, and sustainable development-related topics are grouped into a light blue cluster. Finally, topics in the clusters colored purple depict issues such as resource planning, urban areas, and urban planning.

Biofuel production is used as a prime example of water-energy-land/food interactions that unfold as synergies or compensations, as well as the competitive usages of land-water that take place in its production (Mwale and Mirzabaev, 2015; Rulli et al., 2016; Bellezoni et al., 2018; Ghani et al., 2019; Lazaro et al., 2021a). Biofuel is considered a pilot project for the successful implementation of a nexus approach (Benites-Lazaro et al., 2020). Importantly, this research on the WEF nexus has witnessed the emergence of a range of studies aimed at understanding (and sometimes attempting to quantify) the consequences of an eventual expansion of biofuel production on WEF resources. Thus, the initial focus of WEF nexus research concentrated on agricultural production links on different scales, from watershed studies to broader regions, such as resource exports (e.g., virtual water) between countries (Rulli et al., 2016; Moioli et al., 2018; Munoz Castillo et al., 2019). Studies have shown that water is the limiting component of agricultural production within the WEF nexus, and its use has been overlooked without considering adequate management, often prioritizing other nexus sectors, such as the production of biofuels (Smidt et al., 2016; Rodriguez et al., 2018; Benites-Lazaro et al., 2020).

Trend 2 (2017–2018): Linkages Between the Nexus and the Sustainable Development Goals

Figure 5 shows trend 2 of the topic evolution in the 2017–2018 period, in which period, following trend 1, topics related to water issues as well as sustainable development are predominant. Other topics follow this tendency, for example, agriculture and land-use, ecosystem, and food security. Studies have emphasized that the WEF nexus approach has played a particularly prominent role in supporting the efficient implementation of the SDGs and promoting the green economy as a guiding principle for maintaining economic growth (Hoff, 2011; Giupponi and Gain, 2016; Terrapon-Pfaff et al., 2018; Simpson and Jewitt, 2019; Olawuyi, 2020). The green economy is considered the "nexus approach per excellence" (Brears, 2018), it seeks to unite under a single banner of the entire list of economic policies relevant for sustainable development, and it proposes to go beyond sectoral solutions and actively address the WEF nexus security in order to reduce access-inequalities of water, energy and food (Hoff, 2011; FAO, 2014; Biggs et al., 2015).

Studies have showed the importance of the interdependence among water, energy, and food systems by considering the WEF nexus as essential and intrinsic elements to human development and sustainability (Biggs et al., 2015; Simpson and Jewitt, 2019; de Andrade Guerra et al., 2020). The WEF nexus is a cross-cutting approach that through an interactive process can guide sustainable pathways to resource security and achieve the SDGs (Benites-Lazaro and Giatti, 2021). Its operationalization outcomes and the interactions of these basic resources could alleviate other issues, such as health, climate change, and biodiversity loss. The nexus approach is linked to SDGs, namely SDG 2 (zero hunger), SDG 6 (clean water and sanitation), and SDG 7 (affordable and clean energy), with synergies to SDGs 1 (no poverty), SDG 3 (good health and wellbeing), SDG 5 (gender equality), SDG 8 (decent work and economic growth), SDG 10 (reduction of inequality), SDG12 (responsible consumption and production), SDG 13 (climate action), SDG 14 (life below water), and SDG 15 (life on land). Therefore, the nexus approach can support sustainable development, with a focus on trade-off reduction and maximizing additional benefits or synergies that outweigh the costs associated with greater integration across sectors.

Figure 5 also shows the predominant topic of food security. Current studies on the driving forces of the WEF nexus in food production have focused on different scales and methods (Kajenthira Grindle et al., 2015; Li et al., 2019; Zheng et al., 2022). For some proponents, because food production consumes a lot of water and energy, the food dimension can be regarded as the center of the WEF nexus (FAO, 2014; Zheng et al., 2022). Other studies related to food security from the WEF nexus perspective have discussed the competitive uses of natural resources such as land and water for food or energy production, specifically biofuels (Rulli et al., 2016; Benites-Lazaro et al., 2020). These

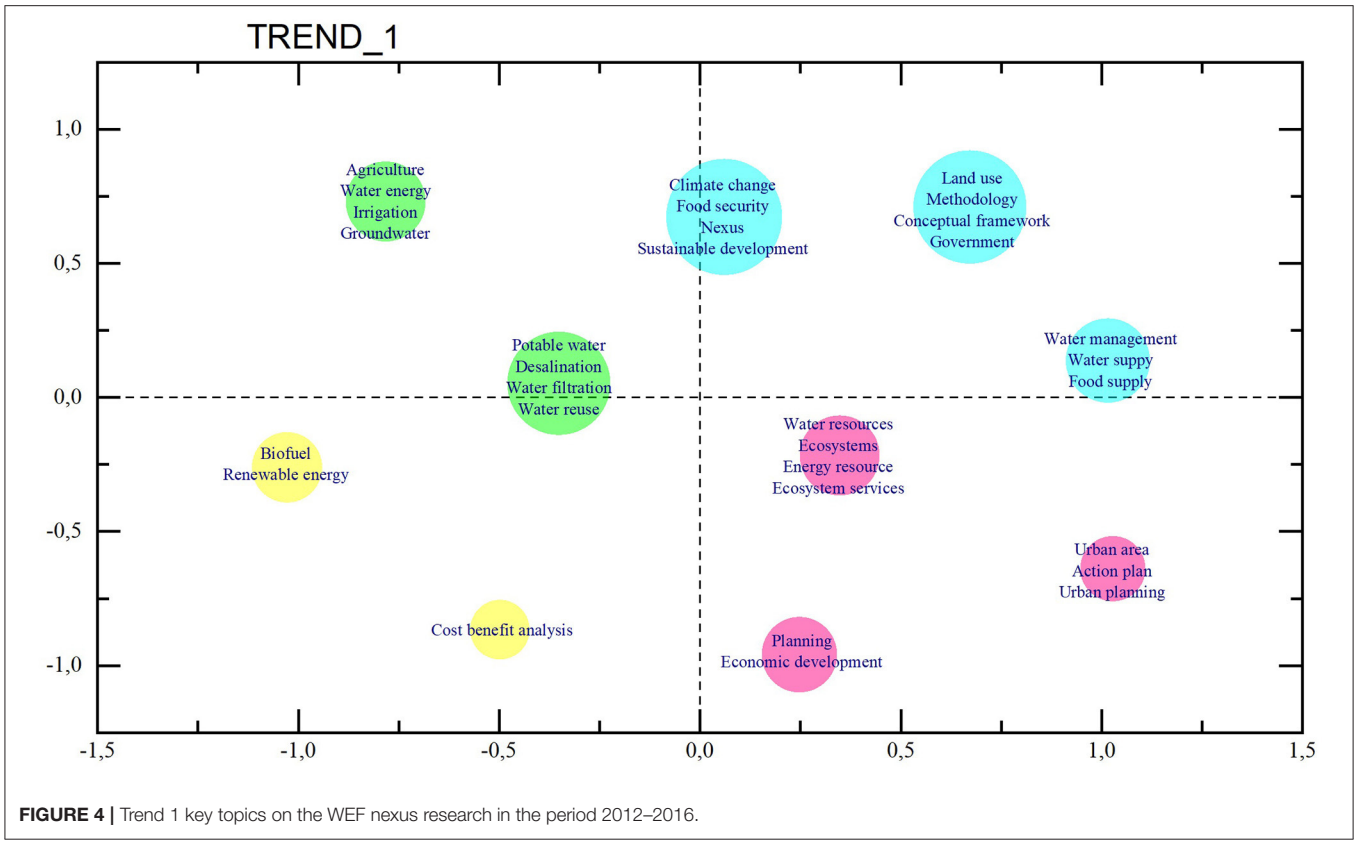

FIGURE 4 | Trend 1 key topics on the WEF nexus research in the period 2012–2016.

studies uphold energy, food and water security as being closely related to complex environmental, social, political, and economic matters.

Trend 3 (2019): Nexus Governance and Policy Integration

Figure 6 shows trend 3 (2019), which emphasize topics such as governance, ecosystem, sustainable development, resource management, policy making, and decision making. Some studies refers to the nexus as governance concept that seek integrate resource management and sectors across policies and regulations to promote sustainability and better resource allocation (Kurian and Ardakanian, 2015; Weitz et al., 2017; Märker et al., 2018; Urbinatti et al., 2020). The nexus approach promotes policy integration and coherence by identifying optimal policy mixes and governance arrangements across nexus sectors (Weitz et al., 2017). It perceives integration and interdependence across various sectors as a fundamental step in ensuring resource security in the global context of increasing and competing demands (Artioli et al., 2017; Weitz et al., 2017).

However, implementing integrative governance can be challenging in many countries where institutional capacity is limited, and where there is a prevalence of conventional actions and policies characterized by decision-making in "silos" (which favors isolated sectors) (Weitz et al., 2017; Pahl-Wostl, 2019). For example, the study by Benites-Lazaro et al. (2020), which analyzed the Brazilian case, showed that nexus governance challenges are only partially considered in government structures, and their implementation remains a challenge in any fragmented institutional setting. Silo regulatory solutions prevail, and the tradition of planning and governance has been maintained in sectoral dynamics. The difficulty of each sector in implementing its own objectives is aggravated not only by the lack of connection between sectors, which in practice are already interconnected but also by the limited institutional capacity of institutions. Pardoe et al. (2018) showed that the Tanzania National Adaptation Plan of Action (NAPA) was an important milestone toward a change in sea levels in the integration of climate change into sectoral policies and plans. However, Pardoe's study shows that crucial cross-sectoral collaboration to implement climate change mitigation and adaptation strategies remains limited due to institutional challenges, such as power imbalances, budget constraints, and an entrenched-silo sectoral focus. Another study by Stein et al. (2018) described the interactions of the WEF system and the actors that influence these systems in the Upper Blue Nile region of Ethiopia, showing that the stakeholders in each WEF sector are not isolated from each other but rather embedded in hierarchical structures. These centralized governance structures can help explain why coordination challenges persist despite the cross-sectoral relationships among them, and also demonstrate the challenges in the governance of WEF systems.

The nexus approach focuses on policy coherence and integration. This is the systematic and dynamic identification

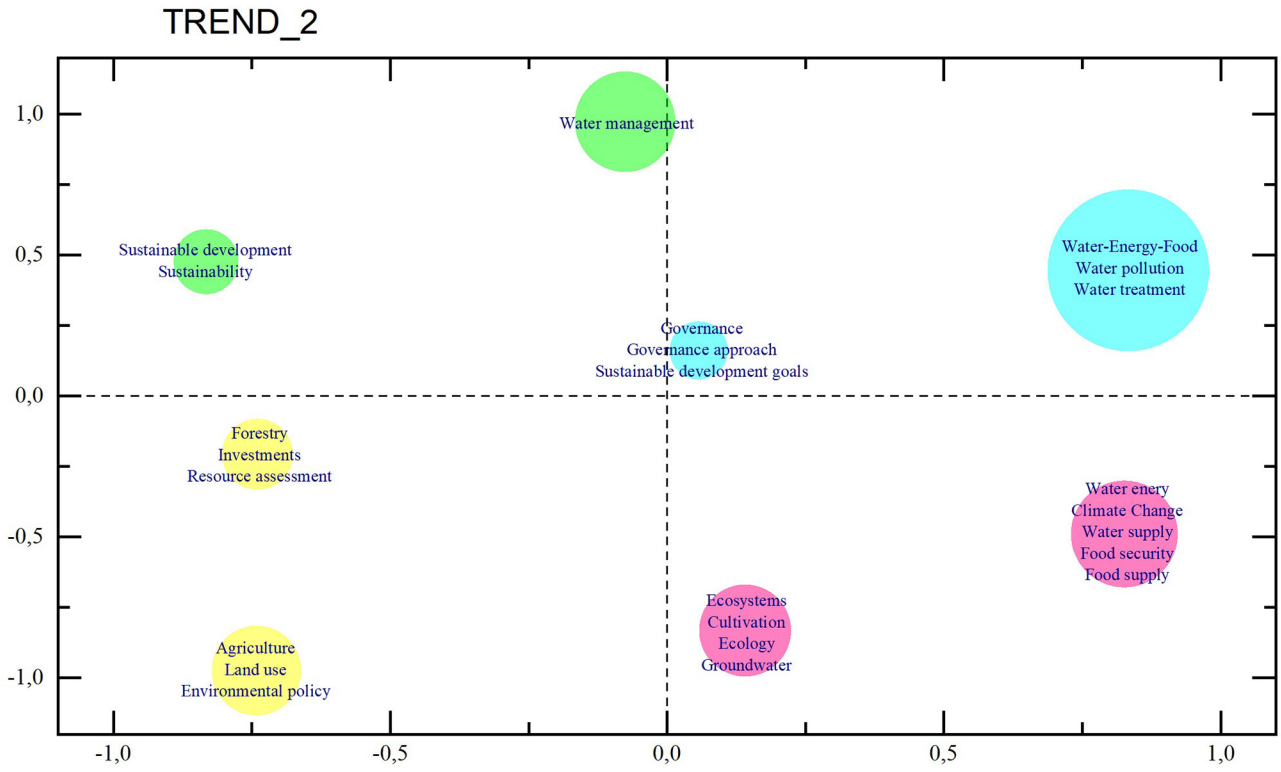

FIGURE 5 | Trend 2 key topics on WEF nexus research in the period 2017–2018.

and management of trade-offs and synergies between policies across sectors (Lazaro et al., 2021a). Existing studies show that "policy coordination" between various stakeholders, at all levels in general and at the local level in particular, governing the water-energy-food nexus is the key to promoting equitable allocation and access to the WEF (Sharma and Kumar, 2020; Rasul and Neupane, 2021). However, the effort to reconcile the fundamental objective of policy coordination and integrated governance in the WEF sector is in progress, and many questions about policy applicability, solid legal structures, and the political performativity of nexus thinking remain unanswered (Lazaro et al., 2021a).

Previous studies, such as Sharma and Kumar (2020) describes that policy coordination among all WEF nexus sectors, actors, and at all levels (multi-scale sector and multi-actors) is the key to promoting equitable resource access and allocation. To this end, legitimate governance with robust legal structures and effective stakeholder participation in the governance of nexus sectors is necessary to provide equitable resource allocation. In a similar vein Hagemann and Kirschke (2017) emphasizes that governance to promote synergies and mitigate trade-offs arising from resource constraints within the WEF system requires actor constellations and heterogeneous institutional frameworks that can vary depending on the context and phase of the political process. Mainly, with respect to the policy and decision makers, Mohtar and Daher (2016) refer to a lack of access to a set of comprehensive tools that: i) correspond to the nature of the nexus, they are multi-stakeholder and multi-scalar from local to regional, national, or global, ii) are capable of defining and quantifying the interconnectivity between WEF resources, and iii) are capable of including integrated and holistic management strategies to address planning for the allocation of these resources.

Policy coordination and harmonization of objectives for WEF nexus policies is, therefore, a daunting task that requires the involvement of key stakeholders, acknowledgment of different perspectives and priorities, and development of a shared understanding of what needs to be achieved (Rasul and Neupane, 2021). Hoolohan et al. (2019) suggest that integrating different forms of knowledge, such as rigorous analysis of case studies, stakeholder interviews, and agent-based modeling, can contribute to decision-making and policy. Thus, governance analyses should refer to different types of problems instead of focusing on single cases and abstract analyses. This facilitates the transfer of results to various contexts, and we can only find answers if the call for inter-and trans-disciplinary research is taken seriously, going beyond the sheer knowledge of any individual researcher. In addition, nexus approaches provide a concrete framework for the ongoing learning property of complex adaptive systems, thus involving social actors from different areas and organizational levels.

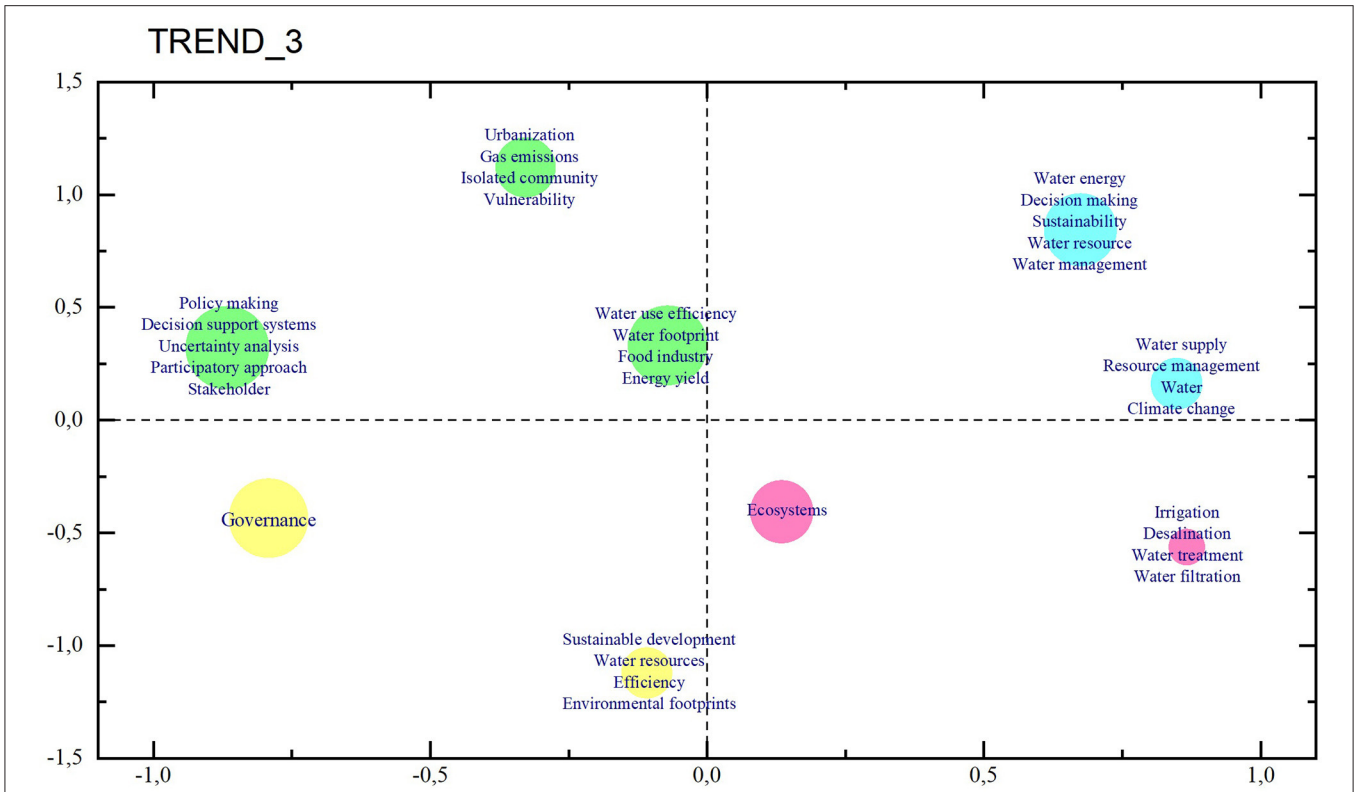

FIGURE 6 | Trend 3 key topics on WEF nexus research in the period 2019.

Trend 4 (2020): Application of the Nexus Concept at Different Scales

Figure 7 shows trend 4, in this period we identify studies applied to different scales, mainly there increasing research of the nexus at urban and city scales, and coupled topics such as circular economy, waste and WEF nexus, resilience, and smart cities. For example, in the circular economy, and waste–WEF nexus, an alternative to the current economic model, the circular economy is directly linked to a more sustainable development and has as its focus on the efficient use of resources and the minimization of waste generation, seeking to maintain the flow of material and energy at their highest level and for a maximum time (Geng et al., 2019). A circular economy can generate WEF co-benefits and bring together intersectoral collaboration to generate solutions to contemporary problems, such as solid waste and wastewater (Puppim De Oliveira, 2013; Del Borghi et al., 2020). The circularity of these streams could be expanded by connecting them with other sectors, further providing more opportunities for WEF provisioning and security. In this regard, a circular economy is intrinsically related to the WEF nexus approach, as both aim to contribute to reducing environmental degradation and its effects on resource security and climate, while promoting economic growth (Laso et al., 2018; Lehmann, 2018). As for the WEF nexus logic, systemic changes are needed for a transition from linear to circular systems to have a larger impact on WEF securities, requiring efforts at different levels of action and with the involvement of national, regional, and local government authorities (Ghisellini et al., 2016).

Driven by such integrated approaches, economies may benefit from a transition toward a circular economy that uses renewable resources and designs cyclical and efficient systems for provisioning WEF. Decentralizing waste management saves energy, water, land, and emissions, and reduces material waste. Thus, curbing food and water waste will contribute to lowering the overall energy use. Therefore, the circular economy is well suited to dealing with material supply risks, which are particularly pertinent to WEF security. For example, Lazaro et al. (2021a), have described that the linear agricultural economy can be transformed into a circular agricultural economy by minimizing water and energy consumption in food production, by using modern irrigation techniques, and reusing and recycling the agricultural waste in the form of biofertilizers. Some initiatives on the circular economy described by the bioenergy sector in Brazil are in the use of by-products as inputs for cogenerate electricity and the reuse, recovery, and recycling of materials and energy such as water reuse management, effluent management, use of vinasse as fertilizer, and crop rotation with grains that provide sugarcane productivity benefits (Lazaro et al., 2021b).

The study by Lehmann (2018) showed three specific cases on the implementation of circular economy and the urban nexus

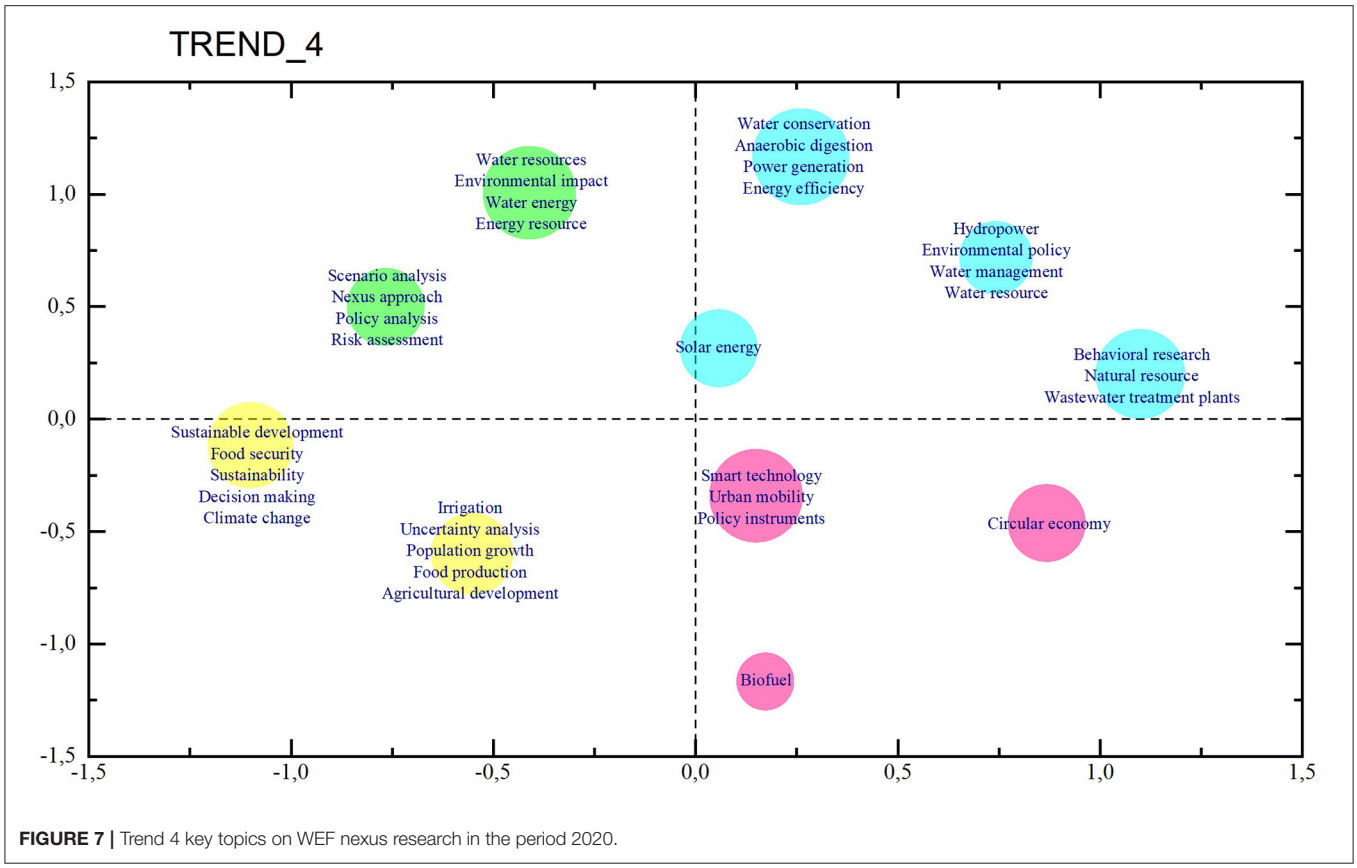

FIGURE 7 | Trend 4 key topics on WEF nexus research in the period 2020.

approach relating to energy, water, food and waste/material flows. Pekanbaru, Indonesia, the city implemented the project "New Landfill: Solid Waste to Energy Project." The project entails the improved management of the sanitary landfill and the installation of an efficient methane gas collection and energy production system. Naga, Philippines, using the urban nexus approach, implemented a system for the production of energy from wastewater in the form of biogas and the reuse of treated wastewater for irrigation in agriculture. The urban nexus project in Nashik, India, focused on implementing efficient management and optimized use of energy and groundwater to limit the impacts of these scarce resources on farmers. This pilot project demonstrated a successful example of synergy and well-coordinated planning that improved resource productivity and economic gains from energy efficiency resulting in lower energy bills.

The nexus approach and circular planning for WEF sectors can increase resource flow capacity, reduce consumption, optimize production at local and regional levels, and add value to the WEF supply chain. Such integration optimizes planning for the use of resources, contributing to greater efficiency in industrial processes and infrastructure development, with consequent reductions in carbon emissions and waste generation (Lehmann, 2018; Feng et al., 2020). Local, regional, and national organizations can promote integrated planning through circular economy principles and the WEF nexus approach, focusing on improvements at the micro-meso-and macro-scales. Individual businesses (e.g., micro trades) can gain efficiency through internal circular models (e.g., material reuse). There are many opportunities for a more integrated economy at the meso level (e.g., industrial symbiosis). Finally, connections at the macro level, such as national energy or climate policies, can consolidate opportunities to further expand integration initiatives across the WEF sectors to combat climate change. Thus, expanding the nexus approach at different scales, and focusing on the impacts on the supply of scarce resources and the pressures exerted by climate change requires the involvement of stakeholders at different levels of action and with the engagement of government authorities at all levels.

Trend 5 (2021): Nexus, Climate Change and Urbanization Challenges

As represented in **Figure 8**—trend 5 (2021 period), studies mainly show that urbanization and its links with climate crisis and global environmental challenges have made the WEF nexus approach a key element within debates on natural resource management, policy, and governance. Responding to the unsustainability challenges ahead becomes ever-more urgent and will require changes in the way societies manage and consume their resources. The nexus concept has become increasingly important in the urban context (Artioli et al., 2017; Lee et al., 2017; Covarrubias, 2019). Most of the urban population

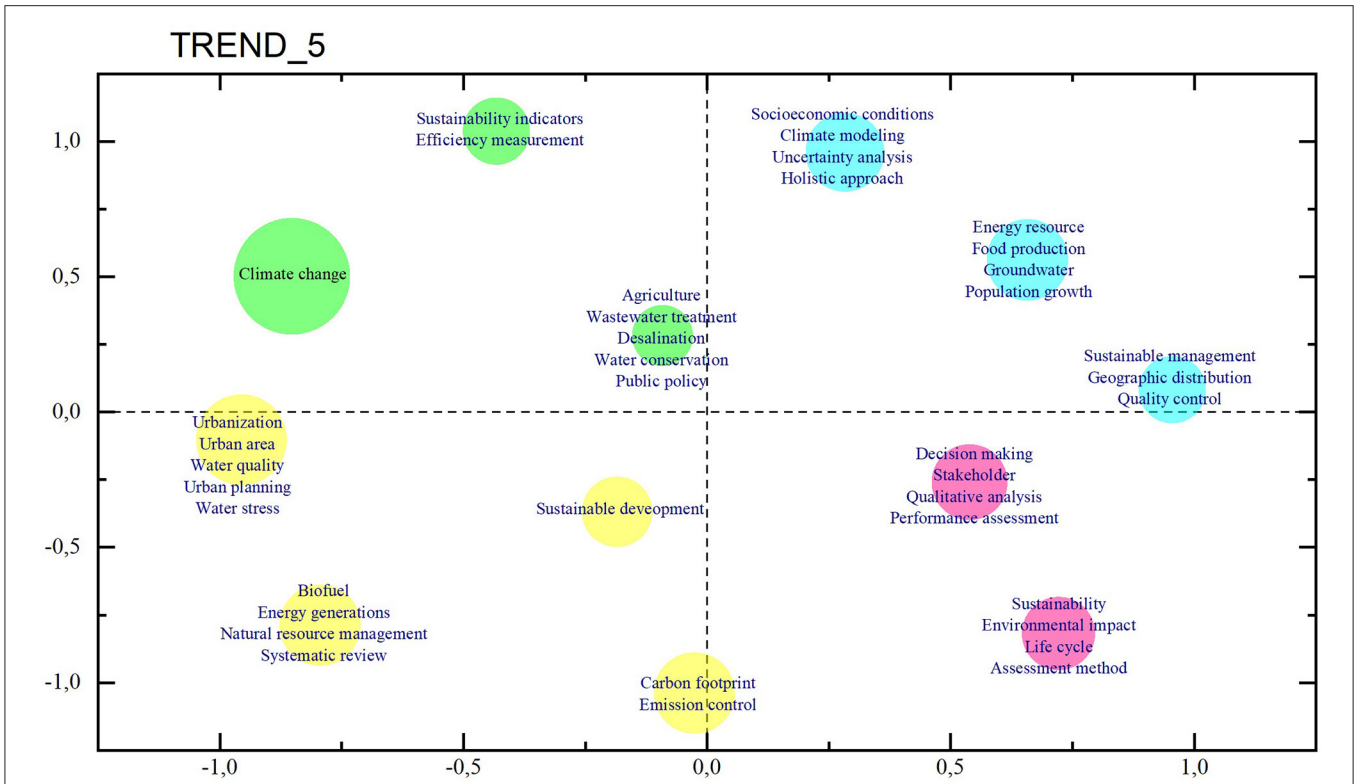

FIGURE 8 | Trend 5 key topics on WEF nexus research in the period 2021.

and consumption are concentrated in cities, which are dependent on hinterlands for WEF to sustain urban activities. Furthermore, the supply disruptions and immediate effects of COVID-19 on the provision of water-energy-food at the urban scale were aggravated in this pandemic context (Al-Saidi and Hussein, 2021).

With the projected growth of the urban population and consumption, the demand for natural resources will increase, stressing WEF systems. This urban demand for resources results in tension with neighboring communities, resulting in unwanted environmental impacts. Thus, we expect that a growing concern about the urban context will have reflect on the topics explored in the WEF nexus literature, which has historically had its origins in the agricultural sector, such the WEF nexus of biofuels discussed above. Therefore, a better understanding of the interests and institutions behind urban nexus research could help highlight and increase capacities to make changes and foster governance at the local scale, with the ultimate goal of increasing WEF security.

The transition from studies on the rural to the urban WEF nexus is therefore understandable and justified by the fact that cities are supported by resources coming mainly from rural regions, located far from consumption centers. Cities are often characterized by unsustainable patterns of consumption and production, which contribute to environmental degradation and injustices (Amaral et al., 2021). Urban demand for resources results in tension with neighboring communities, which exacerbates unwanted environmental impacts, especially climate change. In this regard, the WEF nexus approach can contribute to a better understanding of the potential connection between cities and rural areas, increasing capacities to promote changes and fostering governance at local and regional scales, with eventual positive impacts on WEF systems (Seitzinger et al., 2012; Artioli et al., 2017).

FINAL REMARKS

How Has the WEF Nexus Literature Evolved Over Time?

Our study identifies that the literature on the WEF nexus has been extensively outlining the failures in the planning and management of these resources, stressing the importance of considering both the interdependence between sectors and their indirect and transboundary effects. Motivated by the IWRM approach to water management and the repercussions caused by the Bonn 2011 Conference, researchers and policymakers have been striving to refine and spread the nexus approach to understand the trade-offs and synergies in the supply and demand of WEF resources. While it has potential strengths, the understanding, diffusion, and application of this framework also face challenges, particularly with respect to transitioning from its theory and modeling to real-life applications.

Our review points to the existence of different approaches for the WEF nexus that present variations according to the focus component under analysis, with initial focus on the water

sector. We also identified the evolution of nexus approaches over time and their application to different scales, starting from an agricultural context to a more urban approach, and sometimes including elements that go beyond the three basic resources of the WEF nexus. Such evolutions in the application of the concept have a common focus on a transition toward more integrated planning for WEF sectors, regardless of the motivating factor for the analysis. The shift from silo thinking to systemic and integrated planning for WEF requires a complete restructuring of institutions and the way in which society views, exploits, reuses, and disposes of WEF resources. Therefore, it is instructive to examine trends in WEF nexus research, in terms of predominant topics to discover how the evolution of this approach may gradually influence the shift to systems thinking with its application to different scales.

Through the LDA method applied to examine a large amount of information in the literature and map its thematic landscape, it was possible to identify how some studies on the WEF nexus, initially focused on technical aspects to better understand the trade-offs between the sectors. For example, bioenergy production and its impacts on WEF security have begun to include governance elements for these sectors, in addition to examining the institutional and social aspects of the SDGs. These topics are important for a systemic analysis of the impacts of natural resource exploitation, production, and supply but are not fully representative of the broad solution. Thus, an emerging and relevant range of research has been neglected, as the focus was on understanding the impacts of WEF resource supply rather than demand. More recently, nexus frameworks applied at the scale of metropolitan regions and cities have driven the shift to approaches that include other components that directly or indirectly affect WEF systems, such as ecosystem services, waste management, circular economy, mobility, and smart cities.

Moreover, our research approach identified the thematic trends in the literature on WEF nexus post the 2011 Bonn Conference. For example, there is a fast-growing research cluster around topics such as sustainable development, urbanization, renewable energy, climate change, and circular economy. Because some of these topics have been comparatively small in the past, WEF nexus researchers may want to give them more consideration in the future. We also point out that with the inclusion of a chapter on cities in the fifth report of the Intergovernmental Panel on Climate Change, the trend is for this topic to dominate WEF nexus research, as cities are major contributors to the demand for WEF, largely supplied by adjacent regions and with significant negative impact on supply-chain emissions. However, we do not suggest that the fastest growing topics should be the focus of future research, as renewable energy (e.g., biofuels) and sustainable development have already been considered. Instead, our topic mapping exercise is intended to draw attention to relevant issues in discussions on how the nexus approach can be applied to different resources and at different scales through the development of case-specific methodologies and policies.

Policy Development for the WEF Nexus

An IWRM review points out that the integrated water management concept has existed since the early 1990 decade, but has a dubious implementation record, without being critically evaluated. The criticism focused on the fact that contemporary publications that promoted the IWRM approach were not able to identify an implementable process for integration, with difficulties justifying the use of the concept (Biswas, 2009). The main reason for this was the "almost universal popularity of a vague, indefinable, and inexplicable and non-implementable concept" (Galaitsi et al., 2018). Similarly, the WEF concept appears to struggle with the same issues of coherence.

Despite the evolution of the topics, WEF nexus research has presented some difficulties in defining universal approaches, methods and tools in the field, in addition to a deficit in the inclusion of socioeconomic analyses, particularly on the actors and institutions that shape access, distribution, and use of WEF resources (Newell et al., 2019). This difficulty of universalization lies in the fact that applied WEF nexus frameworks require that the structure of WEF systems be sized for specific cases, aiming at different evaluations and applications, as well as be useful for policy implementation and decision making. The availability of complete and relevant data also poses a challenge for the practical implementation of the WEF nexus on any scale of interest, which is viewed as a weakness by some researchers (Simpson and Jewitt, 2019).

Ideally, the WEF nexus literature would provide a platform for converging multiple streams of research, identifying linkages and complementary policies. For example, ecosystem services promoted by nature-based solutions, such as urban agriculture, strategically located in regions with high demand for WEF and low local supply, could provide residents with the option to purchase (or even produce) these resources locally. This would contribute to changes in consumption habits in the medium to long term, with immediate effects on transboundary demands for WEF and their associated emissions. This suggests an important avenue for future research toward integrating policies for land use, urban development, circular economy, renewable energy, and WEF demand and supply planning for additional benefits at different scales for resource security instead of focusing on sector-specific options alone.

Therefore, on the one hand, more cooperation and integration between WEF sectors as well as between different governmental levels is needed to promote the positive effects of the nexus approach in the planning of food, water, and energy systems. In practice, we need to develop multilevel sector integration to better understand the policy challenges of applying a conceptual idea in the real world, in the form of. learning-by-doing. Advancing the desired sustainability in the use of scarce resources should not necessarily depend on public policies and initiatives, and be better understood, designed, and disseminated by researchers and decision makers. On the other hand, there is the need to study the results of these practical trials to advance the science on how the nexus approach can solve issues that emerge in its application. It would be a process of going back and forth from science to policy and vice-versa. Thus, the two-way linkage

between science and nexus policy can be improved by further digging into the science of nexus by learning from its application, which tends to have results very dependent on the context. In this sense, despite its limitations, the evolution of the applications of the nexus concept over time has value in allowing it to be adapted to different perspectives and interests, enabling easy inclusion of emerging Research Topics.

AUTHOR CONTRIBUTIONS

LLBL: data curation, writing—original draft preparation, conceptualization, methodology, and software. LLG: writing—original draft preparation, visualization, investigation, methodology, and writing—reviewing and editing. RAB: writing—original draft preparation and editing. JAPO: methodology and writing—reviewing and editing. PRJ: writing—reviewing and editing. All authors contributed to the article and approved the submitted version.

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