



Review

Analysis of Pros and Cons in Using the Water–Energy–Food Nexus Approach to Assess Resource Security: A Review

Somayeh Rezaei Kalvani *  and Fulvio Celico 

Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parco Area Delle Scienze 157/A, 43124 Parma, Italy; fulvio.celico@unipr.it

* Correspondence: somayeh.rezaeikalvani@unipr.it

Abstract: The water–energy–food (WEF) nexus is drawing much attention in scholarly literature as a novel alternative to address complex resources and achieve resource security. The aim of this study is to analyze and review existing nexus studies to investigate the current status of nexus research worldwide. This study used a narrative review approach to provide a comprehensive overview on the WEF nexus using a variety of databases. It is indicated that the majority of studies in Asia and Africa focused on the water–energy–food (WEF) nexus. China and Brazil had the largest nexus research. Based on the existing literature, most of attention has been paid to food production. However, food consumption patterns and dietary change are rarely evaluated, and there is a lack of study on impacts of dietary change on the WEF nexus. Moreover, there is a lack of frameworks for the evaluation of the WEF nexus under dietary change scenarios. The major challenge of the nexus approach is data availability in crop production, which can be solved by using remote sensing data. There is a lack of standard and conceptual frameworks for nexus assessment and, then, an essential need to provide a new holistic and standard approach that be applicable worldwide to increase connections between researchers and decision makers, as well as the applicability of nexus approaches. Future research must couple the development of a holistic standard approach with experimental tests in different areas, involving interdisciplinary research groups able to carry out all the experimental activities, the numerical simulations, and the statistical analyses of climatic time series (in a climate change perspective) indispensable to demonstrate the real benefits of using a WEF-derived nexus approach.



Citation: Rezaei Kalvani, S.; Celico, F. Analysis of Pros and Cons in Using the Water–Energy–Food Nexus Approach to Assess Resource Security: A Review. *Sustainability* **2024**, *16*, 2605. <https://doi.org/10.3390/su16072605>

Academic Editors: Jiayu Xu, Meng Peng and Hongzhang Xu

Received: 4 February 2024
Revised: 15 March 2024
Accepted: 19 March 2024
Published: 22 March 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: water–energy–food security; remote sensing data; climate change adaptation; sustainable development goal

1. Introduction

The WEF nexus provides an integrated method to analyze and trade off between different resources in order to increase resource-use efficiency and adapting optimal and ideal policies [1]. The root of the word ‘nexus’ is from *nectere* in Latin, which means to bind and indicates a relationship between two or more items [2]. The water–energy–food nexus is the assessment of connection or interaction between these three elements [3]; for instance, the foundation of food production requires water for growing crops, and this water needs energy for pumping water and water treatment, and in return, energy production relies on water [2,4]. The WEF nexus approach contributes to moving sustainability forward by managing stress with measurements based on the idea that it is not possible to achieve WEF security in an isolated way in a practical and powerful manner without regarding the interaction between them [5,6]. The nexus method is created based on the management of these resources separately that leads to unplanned water stress, which does not support sustainable development goals [7]. Moreover, in practical terms, it provides the conceptual method to better grasp and systematically analyze the interaction between human activities and natural environments and move forward a more coordinated management of resources among sectors. This can contribute to managing and bringing trade-offs

and create synergies, allowing for more cost-effective alternatives, implementation, and monitoring [8]. The nexus can be conducted at different scales, such as household [9,10], urban [11], agricultural [12], country [13,14], and transboundary scales [15,16]. Applying a WEF nexus in transboundary water resources can help to solve water crises and to enhance mutual collaboration among different countries [15]. Moreover, it provides cooperation opportunities in shared water resources [17] and provides flexible solutions for water crises [15].

According to the FAO (2014), a nexus is a novel method for supporting food security and sustainable development in the agricultural sector by concentrating on reaching zero hunger (SDG2), water sanitation and clean water (SDG6), and accessible, clean, and cheap energy (SDG7) [18]. Other scholars claimed that a nexus is a new approach for sustainable watershed management since a watershed is a complex and dynamic ecosystem and applying a holistic nexus as a soil–water–energy–food nexus can help to increase resource security and reduce resource vulnerability [19]. According to Smajgl et al. (2016) [20], a nexus is a novel method for supporting sustainability in the agricultural sector and increasing food security [21]. The WEF nexus is a fairly novel approach and is under development for policymaking [22]. However, other scholars argue that the nexus concept is not novel [23–25], expressing that a conference in 1977 (UN, 1977) disclosed that the concept of a nexus was used earlier as interlinkage between water, energy, and food. Moreover, Benson et al. (2015a) claimed that many elements in the nexus were presented earlier in other methods in the 1990s [23]. Simon (1987) [26] claimed that there is a connection between food, energy, environment, and demography, and they cannot be treated separately. This information confirms that a nexus is a novel approach for food security and sustainable development, while the concept is not novel for the assessment of interlinkage and interaction between the resources since it was used earlier.

The WEF nexus was initially introduced in November 2011 as a solution to achieve sustainable development goals and a green economy [27]. After the Bonn conference, a nexus has been defined in different ways according to the study scope—for instance, by including climate change as one part of the nexus approach (UNEP, 2017). Various approaches, theories, and concepts have been developed to evaluate the connections between water, energy, and food, such as [8,28–33].

In spite of a dramatic increase in publications on the WEF nexus, a comprehensive literature review on the WEF nexus is not sufficient. More studies are needed to address the complexity of the WEF nexus. Understanding strongly published articles helps to find the research gaps and modify the framework. This study provides a comprehensive overview of the existing nexus study at the global scale, which helps researchers to understand the current status of nexus studies, identifies the research gaps, and provides valuable information for future research.

The objective of this study is to answer the following research questions:

- How many frameworks exist worldwide and why?
- Is the spectrum of frameworks related to the need to answer different questions in different socio-economic and environmental settings?
- In which countries have nexus studies been mainly developed and why?
- Is climate change taken into account in nexus studies and how?
- On the whole, what types of nexus approaches are available in the scientific literature?
- Finally, which are the main research gaps and limitations in actual nexus methods?

2. Materials and Methods

This study used a narrative review by using scientific research papers from before 2023. The following stages have been done [34]:

1. Conducting a search by using different databases that can cover all of the related papers. It was necessary to use a variety of databases to make sure that all of the relevant databases have been included. Scopus, Web of Science, PubMed, Google Scholar, and Science Direct were used as databases because they are secure databases.

Only research in English was considered. Unpublished abstracts, articles, reviews, and dissertations were excluded.

2. Finding suitable keywords that can help to solve research questions.
3. Review papers: the process of selecting relevant papers involved assessing exclusion and inclusion criteria and quality evaluation. In the initial stage, the abstract and title were used to find relevant studies. Non-relevant papers, as according to the abstract and title, were omitted. Then, the relevant papers that can address the research questions were reviewed.
4. Summarizing the results: all of the results were written and summarized [34].

This study used more than 300 published papers. The search was conducted using the following keyword: WEF nexus, WEFL nexus, WEFC nexus, WEF security, WEF nexus in seafood, WEF nexus in livestock, WEF nexus in crop production, WEF nexus and ecological footprint, water quality and nexus, and soil and WEF nexus.

3. Results

3.1. Overview on Different WEF Nexus Frameworks

The nexus method is not a mature approach [25] and not practical in application [35]. It does not have common frameworks and standard approaches [23,36,37]. Some scholars [25,38] advised that applying the nexus approach with many stakeholders for policy making leads to slowness and delays. The application of a complex nexus is not successful because of a lack of data availability [39]. Researchers undertook more effort for producing frameworks with a focus on investigation and connection between water, energy, food, and policy. The first guideline for the WEF nexus was provided by Hoff in 2011, who explained how water, energy, and food security can be achieved by increasing resources efficiency. In the Bonn approach, the global trend of urbanization, climate change, and population is considered to enhance sustainable growth and a productive environment and to accelerate access to safe water [3]. The framework from the Bonn conference was identified as a solution for a green economy. The aim of this framework is to sustain the ecosystem by reducing ecosystem stress. The problems associated with the Hoff framework included the following: 1. lack of a database on the availability of water resources; 2. lack of information on the impact of hydropower on aquatic ecosystems; 3. data for energy consumption is not sufficient.

A food–water–energy (FEW) nexus was produced for the Himalayan ecosystem [28]. The ecosystem was investigated as an important factor in this framework that leads to an increase in resource security. Sustaining Himalayan ecosystem services is essential for upstream and downstream WEF security. This framework provides policies and alternatives for increasing food, water, and energy security in South Asia. The key principles for this framework are the following: 1. restoration of water resources capacity by conservation of soil, wetlands, ice, lakes, and aquifers in the Himalayan ecosystem; 2. developing climate-smart agriculture and providing environmental and social infrastructure for agricultural water management; 3. reducing flood risk in downstream areas; 4. sufficient investments for managing Himalayan water resources and biodiversity; 5. providing a mechanism to encourage mountain communities in managing the Himalayan ecosystem.

Another framework was established to fill gaps in existing frameworks (including the need for a stronger emphasis on creating an integrating method, policy, and investment) by [7]. This framework provided policies and an integrated method. It emphasized implementation and provided practical implementation guidance for decision makers for future policies. It included four steps: 1. evaluating the water, energy, and food security system; 2. proposing future landscape scenarios; 3. investigating future water, energy, and food security; 4. converting the system. Ecosystem management was at the core of the framework. Ecosystem services provide water, energy, and food and their availability and supply. Availability and accessibility were identified as two elements of security. Land was identified as a direct source of human well-being and its interaction with water, energy, and food.

Howells et al. (2013) [30] created a framework as climate, land-use, energy, and water strategies (CLEWs), integrating climate change, water, energy, and land. The policy component was added to this framework using long-range energy alternatives planning (LEAP) (for energy), water evaluation and planning (WEAP) (for water modeling), and agro-ecological zooming (AEZ) (for land use). The interactions between these resources are important since ignoring the interactions between water, energy, food, and land leads to incoherent policy, and policy and strategy impact on other resources. This integrated approach considered the security and vulnerability of water, energy, food, and land under change in precipitation with providing better policy and strategy. This framework not only considered interactions between water, energy, food, and land but also provided valuable information for climate change adaptation.

Another framework was produced by taking into consideration political and physical factors and considering the transboundaries of rivers (UNECE, 2015) [31]. The water, energy, food, and ecosystem nexus framework was produced with the aim of promoting transboundary cooperation by recognizing intersectoral synergies. This methodology is applicable in many various basins with different conditions. It is sufficiently flexible, which is applicable at a global scale or in specific conditions. This method is able to produce policy options to solve conflicts among multi-use resources. It helps to increase resource-use efficiency and ensure policy coherence and co-management. For modifying the nexus evaluation, the connection between water, energy, food, biodiversity, and climate change in respect to economic, social, and recognizing policy was added to the nexus approach [31].

Forest was added to the WEF nexus, and the water–energy–food–forest nexus was produced. Only two studies added forest to the WEF nexus and created the water, energy, food, and forest nexus (WEFF nexus) [40]. Forest is one of the most crucial ecosystems on the Earth and the main source of food, water, energy, and food [32]. Agricultural growth endangers forest ecosystems; deforestation as a result of expansion of crops leads to biodiversity degradation [32]. Considering forest in the nexus approach is important because of some threats faced by forests, like deforestation, land shortages, and land degradation. Moreover, forest and landscape restorations are promising strategies for increasing water, energy, and food security [40]. The key principle in the WEFF nexus framework by [40] is the engagement of the local community. The aims of this framework are the restoration of degraded forest and increasing WEF security from landscapes to the regional scale. This framework helps society accelerate the sustainable development goals, since forest security is identified as the foundation for the sustainability of livelihoods.

The variety of dimensions was added to the WEF nexus by researchers. For example, the environment was added to the WEF nexus, and the water, energy, food, and environment (WEFE) nexus was created to manage the agricultural sector appropriately and achieve sustainable agricultural production [41,42]. For example, Mirzaei et al. (2021) [42] produced a WEFE nexus model to increase the WEF nexus index, reduce the use of chemical fertilizers (including nitrogen and phosphate), and reduce the use of chemical pesticides by taking into consideration balance constraints in groundwater. Another novel WEFE nexus framework was created by Yue et al. (2021) [41] with the aim of increasing renewable energy production, increasing economic benefit, and reducing water and energy footprints. This method was produced to provide policymakers with sustainable agricultural management. The new model as a WEFE modeling toolkit was produced to better understand the impact of agricultural extension on other sectors [43]. It helps decision-makers by providing coordinated agricultural policies and sustainable agriculture transformation. It was a combination of three approaches including environmental modeling (LCA), irrigation modeling (WaSim), and economic modeling (partial equilibrium). It provided policymakers and adding socio-economic analysis for achieving sustainable agricultural production [43].

Hatfield et al. (2017) [33] claimed that soil is the forgotten part of the WEF nexus. In addition. Considering soil in the WEF nexus is essential if we consider soil as responsible for 99% of food production [33]. Soil scholars investigated that soil is one of the crucial components of WEF security. However, the enhancement in soil management is not

sufficient. Soil degradation and soil loss impact food security and lead to unsustainable food production [44]. Besides that, soil erosion impacts water, energy, and food security, and there is interaction between water, energy, food, and soil [33].

Karnib (2017) [45] integrated the WEF nexus method with a stimulatory model (Q nexus model), which is based on input and output theory, that is able to assess the inter-sectoral direct and indirect WEF quantity interaction and optimization method for the appropriate allocation of water and energy use to minimize the total cost, with the aim of optimizing the performance of the WEF nexus. The framework was used for guiding the policymaking to find the best policy options. This model is able to analyze the impacts of model variables on WEF planning decisions. In addition, the model can help determine the best water and energy allocation for reducing the total cost.

Bellezoni et al. (2018) [46] used economic–ecologic input–output (IO) for the analysis of the nexus approach in ethanol production. Water, energy, and land used and GHG emissions were evaluated under different scenarios to investigate the future trends. Karamian et al. (2021) [47] investigated a novel water–energy–food indicator (WEFI) by integrating six indices for management purposes at farm scale. Chai et al. (2020) [48] added new dimensions to the water–energy–food nexus, which were economic, social, and environmental aspects. The impacts of population growth and GDP were evaluated. Li et al. (2020) [12] assessed the relationship between water, energy, and land in livestock to trade off environmental and economic impacts. An optimization (input–output) model was used. In addition, Zhang et al. (2020) [49] applied a coupled optimization model for a synergic WEF nexus. Nhamo et al. (2020) [50] used the WEF nexus to assess resource availability and management to improve livelihoods at the local level.

Xu et al. (2020) [51] evaluated the impact of irrigated crops on the food, energy, water, and CO₂ nexus based on LCA and a metacoupling framework. The aim of this framework was to provide valuable information for management, sustainable food production, and environmental conservation by considering socioeconomic and environmental factors. In this framework, LCA was used for the evaluation of the environmental impacts of crop production including water use, energy use, and carbon dioxide emission throughout three different scenarios. Three footprints (including water footprint, energy footprint, and carbon footprint) were applied.

Higgins et al. (2020) [52] modified the WEF nexus by adding novel terms such as red water and red energy. Red water is defined as the water used for energy production, and red food is described as the agricultural production that is used for energy production. Net primary production (NPP) (change in carbon stock) was also added to the nexus framework. Influencing factors on the WEF nexus such as climate change, demography, and lifestyle were considered.

3.2. Nexus Studies Worldwide

Figure 1 shows the percentages of nexus studies in different countries. The largest studies on the nexus were conducted in Brazil and China. Canada and Russia have few nexus studies, with 0.5% and 0.57%, respectively. The least research on the nexus is in Greenland, Congo, and Ireland. The amount of nexus research in water-scarce countries such as Iran, South Africa, Saudi Arabia, and Lebanon was slightly high, accounting for 2.1%, 1.6%, 1.5%, and 1.5%, respectively, since the WEF nexus is identified as an alternative to managing water demand and water supply [53]. A study by [54] indicated that more nexus studies and research was conducted in water-scarce countries, similar to this result. One nexus study by [55] before the Bonne conference in 2008 was applied in water-scarce countries in Central Asia with the aim of increasing food security. This information confirms that the nexus was initially used in water-stressed countries.

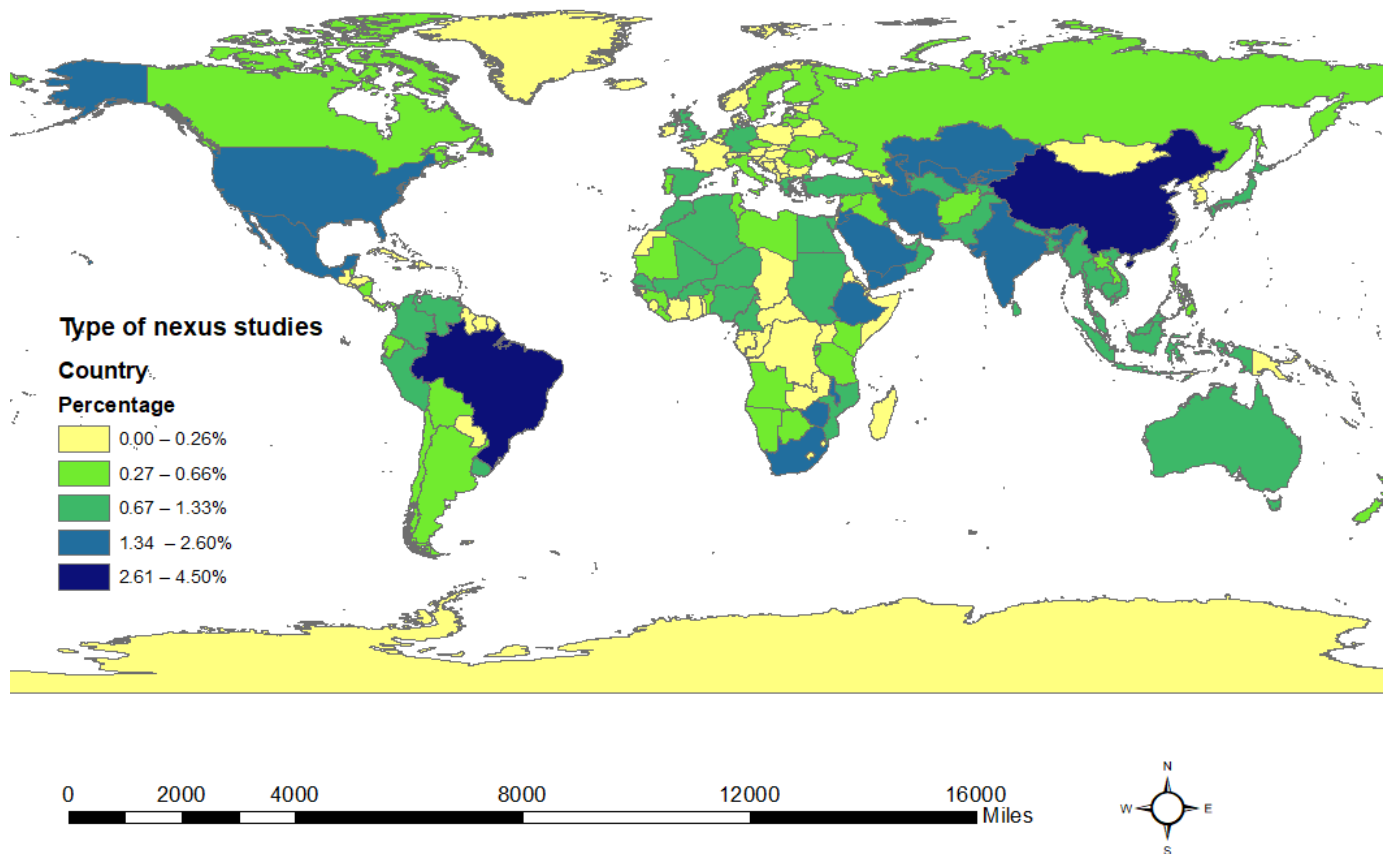


Figure 1. The percentages of the number of nexus studies conducted in different countries.

Figure 2 illustrates the distribution of different types of nexus approaches (WEF nexus, WEFC nexus, and WEFC nexus) in different areas including Asia, Australia, North America, South America, Africa, and Europe. It can be seen that in Asia more focus was paid to the food sector, and the WEF nexus has the largest number of shareholders (81%), while the WE nexus received less attention (9%). In Europe, the largest number of studies (45%) were allocated to the interaction between water and energy sectors because energy production in European countries requires large amounts of water, approximately 21 billion m³ [56]. Moreover, there is an energy crisis in Europe [57], and scholars used the WE nexus to increase energy security and manage water demand and supply appropriately. In Africa, more focus has been paid to the WEF nexus and the climate nexus, accounting for 75% and 62% respectively, while the WE nexus has the lowest proportion (5%). African countries are more vulnerable to climate change due to the low residence, frequent drought, and weak infrastructure. So, considering the impact of climate change on Africa is important because it can provide adaptation strategies and increase nutrition security for future climate change [58].

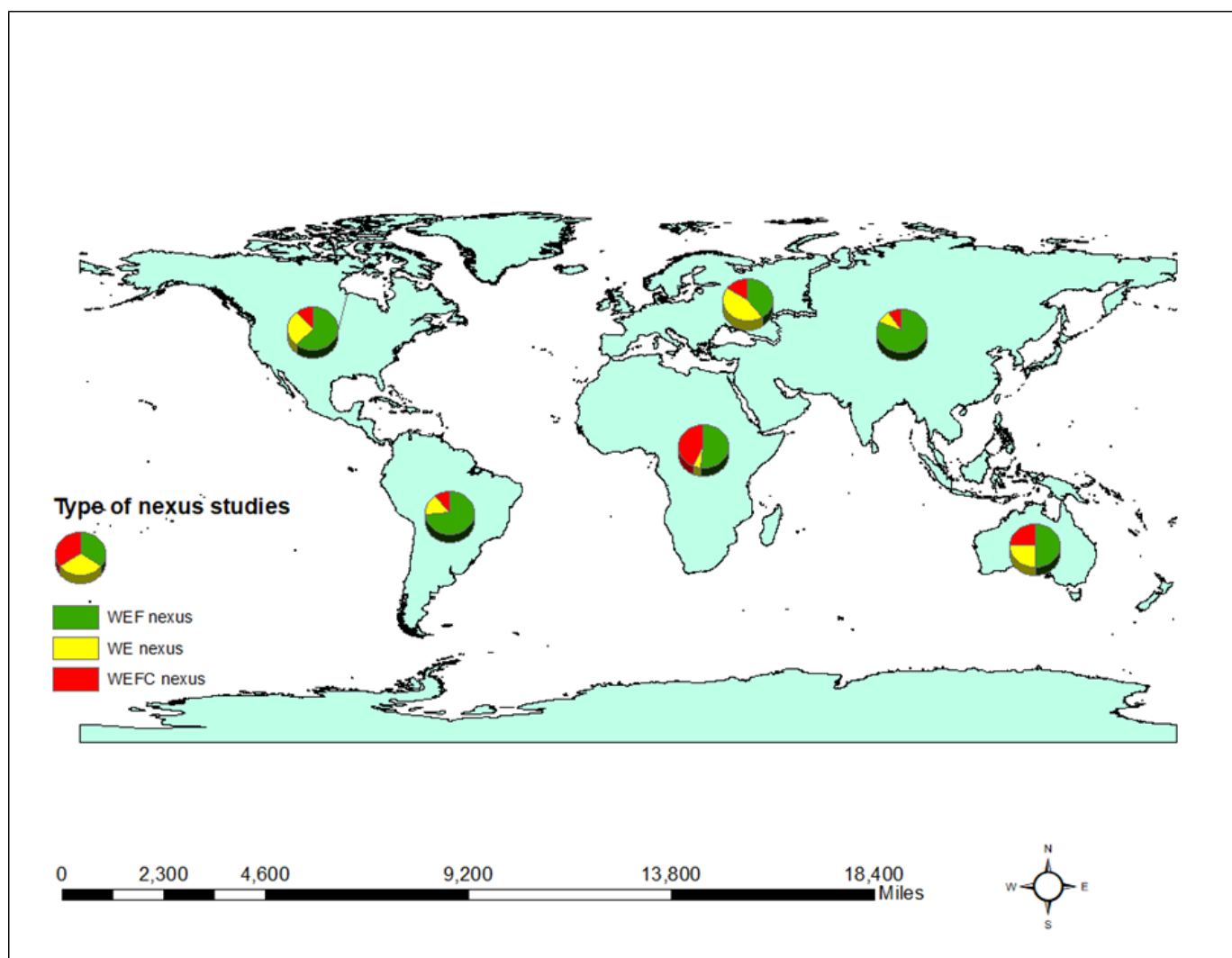


Figure 2. The distribution of different types of nexus studies worldwide (WEF nexus: water–energy–food nexus, WE nexus: water–energy nexus, WEFC nexus: water–energy–food–climate nexus).

3.3. Climate Change within WEF Nexus Studies

Table 1 shows some of the studies on climate change impacts on the WEF nexus. The nexus approach was identified as an alternative for trading off climate change impacts (climate change adaptation) by increasing resource-use efficiency and policy coherence [59]. Climate change impacts on food security by increasing water scarcity and reducing food productivity in arid areas. Climate change models are necessary for assessing the impacts of climate change [60]. The key climate factors that impact on the sustainability of the agricultural sector are temperature and rainfall [61]. Climate change has impacts on the WEF nexus because it leads to some disasters like floods and drought, resulting in reduction in water availability [46,62,63]. Climate change also contributes to increasing temperatures, which lead to an increase in energy consumption [64]. Climate change influences the WEF nexus and fish and wildlife habitats [65].

There are very few studies on the impact of climate change on the WEF nexus. For instance, the WEF nexus as a result of climate change in Arizona was estimated for some crops by the evaluation of a change in crop yield as a result of the change in temperature. It is predicted that an increase in temperature higher than baseline can reduce crop yields by 12.3% and leads to an increase in irrigation of 2.6% per 1 °C increase in temperature [64]. Climate change influences crop yield and food production all over the world. The fifth report by the IPCC shows that crop yield will be reduced in many parts of the world [66].

One study by Liu (2016) produced a new conceptual framework for the impacts of climate change on the WEF nexus and ecosystem in California [65]. Climate change impacts as a result of the change in snowpack, temperature, and precipitation are taken into account [65]. Another study by (Yang et al. (2016) evaluated the impact of climate change on the WEF nexus in Pakistan using the general circulation model (GCM) [67]. The result revealed that hotter and wetter climates can increase pressure on surface water use (because of expansion of crop areas in the model) for crop production. However, a drier and warmer climate decreases the surface water used for crops [68]. Allocation of water resources and using policy for surface water management using a WEF nexus can mitigate surface water scarcity [68]. A climate change method integrated with a nexus is more complicated and sophisticated than traditional models such as SDM [69–71], soil water assessment tools (SWATs) [72], and the SIM4NEXUS model [73,74].

Considering climate change in the nexus approach can help to optimize resource allocations for climate change, to achieve sustainability in water–energy–food, and to increase resource security [75].

Most of the studies used WEAP and LEAP in their evaluation to estimate the current status of the nexus and to evaluate different policies and scenarios. Only limited studies used the system dynamic model for modeling interactions between different resources. A system dynamic approach is an appropriate approach for modeling a nexus since it is able to determine the dynamics between different systems using nonlinear equations [76].

Table 1. Studies on climate change impact of WEF nexus.

Modeling Approach	Country	Nexus Method	Climate Change Scenarios	Author
SDM	Iran	WEFLC nexus	RCP2.5 to RCP8	[77]
WEAP	Arizona	WEFC nexus	RCP4.5 & RCP8.5	[78]
WEAP+LEAP	California	WEFC nexus	GCM (general circulation model)	[79]
WEAP+LEAP	EU	WEC nexus	RC8.5	[80]
Multi-Criteria Decision Analysis+Driver-Pressure-State-Impact-Response (DPS)	The Netherlands	WEFLC nexus		[81]
	Canada	WEFC nexus	GCM (general circulation model)	[82]
	China	WEFLC nexus	RCP	[83]
WEAP-LEAP	California	WEFC ecosystem		[65]
WEAP-LEAP	Turkey	WEFC nexus	different scenarios	[84]
WEAP-LEAP (Multi-Criteria Decision Analysis)	Iran	WEFC environment nexus	RCP8.5 RCP4.5	[85]

3.4. Different Kinds of Nexus Approaches

Researchers use their own methods and frameworks by integrating a new dimension or adding a new influencing factor to the WEF nexus. The nexus are applied in different combinations—for instance as a water–energy–food nexus [86,87], food–energy (FE) nexus [88], land–water–energy–food (LWEF) nexus [89,90], land–water–energy (LWE) nexus [91], and water–energy–land–food–climate (WLEFC) nexus [73,92]. Different geographical areas face different problems related to the three components of the WEF nexus. For example, energy and food security are identified as important issues in the Middle East, and energy is not an essential issue [93]. On the other hand, WEF security is an important issue in North Africa and West Asia [94,95].

The impact of COVID-19 on the WEF nexus was evaluated by many researchers such as [96–104]. Yin et al., 2022, investigated that COVID-19 affected the WEF nexus and led to

challenges on WEF supply and demand [99]. The key alternatives for balancing between WEF supply and demand during the pandemic were the following: 1. promoting facilities and infrastructure for WEF; 2. increasing nature's contributions for the WEF nexus; and 3. improving digital technologies. Moreover, Zhao and You (2021) [98] provided food–energy–water–waste nexus optimization under COVID-19 for alleviation of health and environmental issues, since an increase in food waste became one of the biggest challenges during the COVID-19 pandemic worldwide.

Figure 3 shows the percentages of nexus studies in different food sectors including crops, seafood, and livestock. It can be seen that the most of the nexus studies focused on crop production, accounting for approximately 82%, because agriculture is responsible for more than 85% of human water consumption globally [105]. However, there is lack of studies on seafood production. Only 1% of nexus research evaluated the nexus of seafood production. Assessment of the nexus in the seafood supply chain is important to evaluate the efficient usage of resources throughout their life cycles and to provide policymaking for management and sustainability in seafood production [106]. One study by Gephart et al. (2017) [107] focused only on the interaction between water and seafood as a water–food nexus. However, it is essential to consider energy in seafood production for sustainability evaluation of seafood production since seafood requires energy for production and consumption [106]. Eighteen percent of the research examined the nexus of livestock production. It is necessary to consider land in terms of ecological footprint in crop production with the aim of resource-use efficiency.

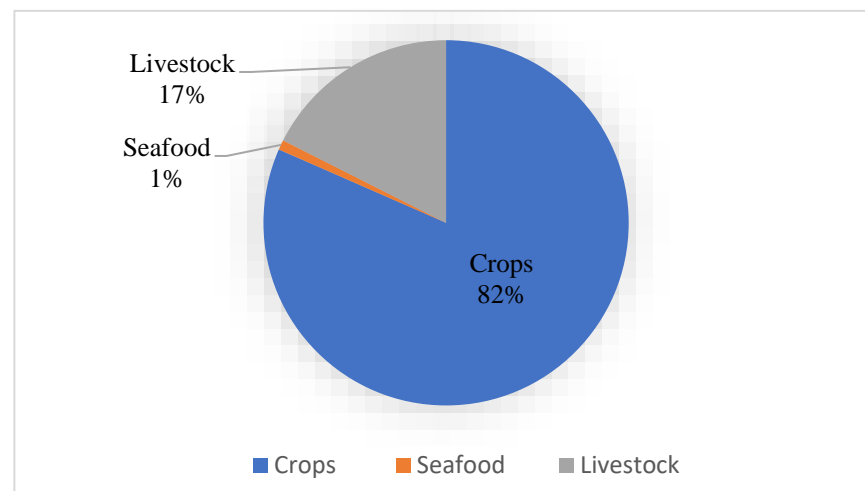


Figure 3. The nexus studies in different food sectors.

3.5. Applicability of the WEF Nexus Approach

Most of the research used a nexus with the aim of increasing resource security, sustainability, and policymaking by comparing different scenarios and alternatives. For example, Jaroenkietkajorn et al. (2020) [108] utilized the WEF nexus to find the land suitable for palm oil production based on resource availability, resource productivity, and resource consumption, using the so-called E and F method. In addition, Fabiani et al. (2020) [109] used a nexus approach to find a more sustainable fertilization method (manual and chemical) in terms of nitrate pollution and WEFL. Moreover, Viccaro et al. (2022) [110] utilized a nexus to find suitable land in terms of efficient use of water, energy, and food for biofuel crop production. In addition, Vahabzadeh et al. (2023) [111] used a nexus to figure out the suitable cropping pattern with regard to increasing WEF security. The nexus approach was also used during COVID-19 to increase food security and handle COVID-19 recovery. Applying the CWF nexus with desalination for water can help to know the future change of desalination of water for crop production while considering social, economic, and environmental aspects. The CWF nexus is a comprehensive approach for sustainability evaluation of

desalination for crop irrigation [112]. Yang et al. (2023) [113] utilized a nexus approach and GIS to find sustainable grain production in different regions of China. Resource security can be increased by using this indicator Gill-Wiehl et al (2023) [114] used the WEF and health nexus in Rwanda and investigated that using solar energy for chilling milk has a low environmental impact and cost. Siyal et al. (2022) [115] utilized the WEF nexus to find hotspots of irrigation for crop production by considering energy and carbon emissions in Pakistan in different districts.

3.6. Main Research Gaps and Limitations in Nexus Methods

In the research field, new approaches and ideas should be welcome due to the fact that different scholars have used different ways in their evaluation. There is no standard, universally accepted method for the nexus approach.

In most LWEF nexus studies, the land has been evaluated in terms of land-use change, land degradation, and land suitability [90]. Additionally, Lazaro et al. (2021) [116] used the LWEF nexus for optimal resource management and policy. Indirect land-use impact by using an ecological footprint needs to be considered in the WEF nexus. An ecological footprint can account for direct and indirect land use (by taking into consideration carbon dioxide emission from fossil fuels by machines) for the agricultural sector [117]. However, there are limited studies that consider ecological footprints in the nexus evaluation. One study conducted by [118] evaluated ecological, water, carbon, and energy footprints in Pakistan in bioethanol production using the LCA and nexus approach with the aim of increasing resource security and environmental performances. The methodology considered nuclear energy and carbon dioxide emissions as indirect land occupation for the evaluation of ecological footprints. Another study [91] took into account the LEW nexus of irrigated and non-irrigated sugarcane production in Thailand by using three footprints including land, water, and energy footprints for appropriate land, energy, and water use. The LCA approach was used to account for both direct and indirect impacts of sugarcane production on land use, water, and energy in different production systems. An ecological footprint was used for evaluation of both direct and indirect land occupations in two different systems. In an irrigated system, the ecological footprint in terms of direct land use was reduced by an increase in crop yield; however, the use of energy and GHG emissions increased in irrigated systems [91].

Most of the nexus approaches focused on water consumption, but water quality is not considered in most of the nexus approaches. Only one study accounted for water quality [119] in a nexus evaluation. Considering water quality in a nexus framework can help to find a suitable solution to achieve sustainable development goals because the environmental issue related to poor water quality leads to other economic and social problems [120].

Food production was evaluated in many nexus studies. There is a lack of studies on the water–energy–food nexus in the seafood sector. More attention has been paid to the evaluation of the nexus of crop production. However, food consumption patterns and dietary changes have rarely been considered in nexus evaluation. In addition, there is a lack of a standard methodology for the WEF nexus under different dietary changes. Considering dietary change with the aim of reducing pressure on the food sector and prompting a sustainable diet is important. Moreover, dietary change can mitigate carbon, water, and ecological footprints [121].

There is an essential need to consider soil in WEF nexus evaluation. Hatfield et al. (2017) claimed that soil is one of the forgotten resources in the WEF nexus. Soil is a finite resource for food production, which can threaten food safety by soil erosion in many geographical areas around the world because of a lack of care and mismanagement of soil. Sustainable soil management is needed to enhance food security, which cannot be achieved without understanding the connection between food security and soil [33]. Moreover, research on land degradation has changed to soil degradation [122]. The soil condition is influenced by land management activities and land use. Indicators for the evaluation of soil

conditions are nutrient content, biodiversity, PH, and carbon content [123]. Moreover, the importance of soil will be clear if we consider the impact of soil erosion on water, energy, and food security.

There is an essential need to provide a database for the nexus in the agricultural sector for all countries with free availability for the researchers by using remote sensing. Remote sensing can provide compatible and regional observations that can help and guide the policymakers and decisions with in situ observations. Different remote sensing products are available to conduct research on water, energy, and food at a regional scale [124]. Only limited studies integrated remote sensing with three component of the WEF nexus [125–127].

Natural resources including water, energy, food, and land are scarce and limited. Unsustainable use of these limited resources leads to increased food insecurity worldwide [3]. The interaction between these resources has been more obvious, and the studies for cross-sectoral efficiency are essential to appropriately use and reduce wastage of these limited resources. However, historically, these resources have been managed separately and independently. There is an essential need to provide a framework to manage these limited resources all together. Most of the existing studies evaluated land as land-use change, land suitability, land degradation, and land condition. So, it is essential to address agricultural land use in terms of ecological footprint to assess land sustainability and land productivity in a WEF nexus study for appropriate resource management and robustness of approach since ecological footprints are able to evaluate indirect and direct land use. Research that integrates agricultural land use with the water–energy–food nexus using nexus and LCA approach is needed to help manage land as a resource [89]. Moreover, with the goal of achieving sustainability, it is essential to consider resources in appropriate quantities.

There is lack of studies on climate change impact on water energy and complex ecosystem process at the regional scale. It is essential to provide a robust framework for nexus policymaking at a regional scale by integrating all five factors, including water, energy, food, land, and climate, to enhance resource efficiency and sustainability, while considering trade-off activity and policy alternatives for the nexus approach.

4. Discussion and Conclusions

There is an essential need to provide a standard and common approach to interface between different policies and science that can solve the challenges of the nexus approaches in terms of applicability by decision-makers [128–130]. Increasing collaboration between researchers, decision-makers, and stakeholders was also mentioned by [130,131] to facilitate undressing the nexus method. A serious obstacle of a nexus is its operationalization and its applicability by government and decision-makers. Financing and funding the nexus timeframes are identified as a research gap. Increasing collaboration between scientific researchers and stakeholders can solve this issue in the first step of producing a framework and guideline [130]. The major challenge of the nexus approach is data availability in crop production, which can be solved by using remote sensing data.

At the same time, this new standard approach must not be influenced by actual and partial/specific needs in selected areas, regions, or countries or by trendy topics but must include all the aspects that can be theoretically useful to analyze and solve problems, now and in the future. For example, in Asian and African countries, more attention has been paid to crop production, crop productivity, and water availability in agricultural sectors. Differently, in European countries [54], more attention was paid to the energy sector by using renewable energy production. However, are we really sure that different continents/countries have and will have different needs? The climate is changing, and people are migrating and will migrate due to climate change, persecutions, oppression of human rights, wars, and so on. Therefore, a new holistic and standard approach must be designed to be applicable worldwide and in a changing world.

The interaction between water, energy, and food is represented adequately in most existing approaches. Differently, some of the major gaps in nexus studies are related to

the hydrogeological aspects of the studied systems, with an emphasis on groundwater dynamics [132]. Therefore, the new holistic and standard approach must also include the experimental characterization of the hydrogeological settings involved in nexus studies. An emblematic case study (actually in progress) is the Parma alluvial aquifer, whose groundwater is used for agricultural (with intensive models prevailing), industrial, and drinking purposes. In that case, water resources can be pumped through purpose-drilled wells at different depths. In fact, the alluvial aquifer is multilayered, and higher permeability horizons can be intercepted within a several-hundred-meter sedimentological sequence [133]. At the same time, some of the irrigation practices are linked to the use of surface water channels. Therefore, on the whole, the same type of human activities (e.g., agriculture) can be linked to really different energy consumption rates, depending on the type of water resources used and the depth at which the groundwater is captured and pumped. On the other hand, the depth of pumping wells can be influenced by qualitative groundwater features, more or less compatible with human purposes. For example, within the same Parma multilayered alluvial aquifer, several studies demonstrated a negative impact from human activities in terms of groundwater contamination (e.g., chlorinated solvents, microplastics, personal care products, and fecal matter) but, at the same time, a diversified impact on shallower or deeper aquifer layers [134–136]. Once characterizing in detail the hydrogeological setting, a statistical analysis of meteorological time series, together with the implementation of a numerical simulation model of surface and groundwater dynamics, can help in understanding if and how much climate change [60] could influence water availability at the medium to long term.

Author Contributions: Conceptualization, S.R.K. and F.C.; research design, F.C. and S.R.K.; supervision, F.C.; formal analysis, S.R.K.; methodology, S.R.K.; project administration, F.C.; writing—original, draft preparation, S.R.K. and F.C.; editing, F.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research benefited from the equipment and framework of the COMP-R Initiative, funded by the “Departments of Excellence” program of the Italian Ministry for University and Research (MUR, 2023–2027).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: We are grateful to the reviewers for their constructive comments and valuable suggestions.

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

Abbreviations

WEF nexus	Water–Energy–Food nexus
WE nexus	Water–Energy nexus
WEFLC nexus	Water–Energy–Food–Land–Climate nexus
WEFC nexus	Water–Energy–Food–Climate nexus
LWE nexus	Land–Water–Energy nexus
LCA	Life Cycle Assessment
GCM	General Circulation Model
SWAT	Soil Water Assessment Tools
WEAP	Water Evaluation and Planning
LEAP	Long-range Energy Alternatives Planning

References

1. Markantonis, V.; Reynaud, A.; Karabulut, A.; El Hajj, R.; Altinbilek, D.; Awad, I.M.; Bruggeman, A.; Constantianos, V.; Mysiak, J.; Lamaddalena, N. Can the implementation of the water-energy-food nexus support economic growth in the Mediterranean region? The current status and the way forward. *Front. Environ. Sci.* **2019**, *7*, 84. [CrossRef]
2. De Laurentiis, V.; Hunt, D.V.L.; Rogers, C.D.F. Overcoming food security challenges within an energy/water/food nexus (EWFN) approach. *Sustainability* **2016**, *8*, 95. [CrossRef]
3. Hoff, H. Understanding the Nexus. In Proceedings of the Background Paper for the Bonn2011 Nexus Conference: The Water, Energy and Food Security Nexus, Bonn, Germany, 16–18 November 2011; Stockholm Environment Institute: Stockholm, Sweden, 2011.
4. Wu, L.; Elshorbagy, A.; Pande, S.; Zhuo, L. Trade-offs and synergies in the water-energy-food nexus: The case of Saskatchewan, Canada. *Resour. Conserv. Recycl.* **2021**, *164*, 105192. [CrossRef]
5. Bazilian, M.; Rogner, H.; Howells, M.; Hermann, S.; Arent, D.; Gielen, D.; Steduto, P.; Mueller, A.; Komor, P.; Tol, R.S.J.; et al. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy* **2011**, *39*, 7896–7906. [CrossRef]
6. Olsson, G. Water, energy and food interactions—Challenges and opportunities. *Front. Environ. Sci. Eng.* **2013**, *7*, 787–793. [CrossRef]
7. Bizikova, L.; Roy, D.; Swanson, D.; Venema, H.D.; McCandless, M. *The Water-Energy-Food Security Nexus: Towards a Practical Planning and Decision-Support Framework for Landscape Investment and Risk Management*; IISD Report; International Institute for Sustainable Development (IISD): Winnipeg, MB, Canada, 2013. Available online: https://www.iisd.org/system/files/publications/wef_nexus_2013.pdf (accessed on 28 March 2023).
8. FAO. *The Water-Energy-Food Nexus at FAO: Concept Note*; FAO: Rome, Italy, 2014; pp. 1–14.
9. Aboelnga, H.T.; Khalifa, M.; McNamara, I.; Ribbe, L.; Sycz, J. Focus: Water—Energy—Food Security Nexus. **2015**, *43*, 1–13. Available online: https://www.entwicklung.at/fileadmin/user_upload/Dokumente/Publikationen/Fokuspapiere/Englisch/Focus_Nexus.pdf (accessed on 2 February 2023).
10. Foden, M.; Browne, A.L.; Evans, D.M.; Sharp, L.; Watson, M. The water–energy–food nexus at home: New opportunities for policy interventions in household sustainability. *Geogr. J.* **2019**, *185*, 406–418. [CrossRef]
11. Artioli, F.; Acuto, M.; McArthur, J. The water-energy-food nexus: An integration agenda and implications for urban governance. *Polit. Geogr.* **2017**, *61*, 215–223. [CrossRef]
12. Li, M.; Fu, Q.; Singh, V.P.; Liu, D.; Li, J. Optimization of sustainable bioenergy production considering energy-food-water-land nexus and livestock manure under uncertainty. *Agric. Syst.* **2020**, *184*, 102900. [CrossRef]
13. Norouzi, N.; Kalantari, G. The food-water-energy nexus governance model: A case study for Iran. *Water-Energy Nexus* **2020**, *3*, 72–80. [CrossRef]
14. Singh, S.; Tayal, S. *Managing Food at Urban Level through Water–Energy–Food Nexus in India: A Way Towards Holistic Sustainable Development*; Springer: Berlin/Heidelberg, Germany, 2021; Volume 24, pp. 3640–3658.
15. Zarei, M. The water-energy-food nexus: A holistic approach for resource security in Iran, Iraq, and Turkey. *Water-Energy Nexus* **2020**, *3*, 81–94. [CrossRef]
16. Kibaroglu, A.; Gürsoy, S.I. Water–energy–food nexus in a transboundary context: The Euphrates–Tigris river basin as a case study. *Water Int.* **2015**, *40*, 824–838. [CrossRef]
17. Elsayed, H.; Djordjevic, S.; Savic, D.; Tsoukalas, I.; Makropoulos, C. Water-food-energy nexus for transboundary cooperation in Eastern Africa. *Water Supply* **2022**, *22*, 3567–3587. [CrossRef]
18. Senzanje, A.; Mudhara, M.; Tirivamwe, L. Chapter 10—The Water–Energy–Food Nexus as an Approach for Achieving Sustainable Development Goals 2 (Food), 6 (Water), and 7 (Energy). In *Water-Energy-Food Nexus Narratives and Resource Securities*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 181–198, ISBN 978-0-323-91223-5.
19. Moghadam, E.S.; Sadeghi, S.H.R.; Zarghami, M.; Delavar, M. Water-energy-food nexus as a new approach for watershed resources management: A review. *Environ. Resour. Res.* **2019**, *7*, 129.
20. Smajgl, A.; Ward, J.; Pluschke, L. The water–food–energy Nexus—Realising a new paradigm. *J. Hydrol.* **2016**, *533*, 533–540. [CrossRef]
21. FAO *The Water-Energy-Food Nexus: A New Approach in Support of Food Security and Sustainable Agriculture*; FAO: Rome, Italy, 2014.
22. Simpson, G.B.; Jewitt, G.P.W. The development of the water-energy-food nexus as a framework for achieving resource security: A review. *Front. Environ. Sci.* **2019**, *7*, 8. [CrossRef]
23. Benson, D.; Gain, A.K.; Rouillard, J.J. Water governance in a comparative perspective: From IWRM to a “nexus” approach? *Water Altern.* **2015**, *8*, 756–773.
24. Muller, M. The “nexus” as a step back towards a more coherent water resource management paradigm. *Water Altern.* **2015**, *8*, 675–694.
25. Wichelns, D. The water-energy-food nexus: Is the increasing attention warranted, from either a research or policy perspective? *Environ. Sci. Policy* **2017**, *69*, 113–123. [CrossRef]
26. Simon, D. Our common future: Report of the world commission on environment and development (book review). *Third World Plann. Rev.* **1987**, *9*, 285. [CrossRef]

27. Martin-Nagle, R.; Howard, E.; Wiltse, A.; Duncan, D. The Water, Energy and Food Security Nexus: Solutions for the Green Economy. Conference Synopsis, (February 12), Inida. Available online: https://wocatpedia.net/wiki/The_Water_Energy_and_Food_Security_Nexus_-_Solutions_for_the_Green_Economy (accessed on 2 March 2023).
28. ICIMOD. *Contribution of Himalayan Ecosystems to Water, Energy and Food Security in South Asia: A Nexus Approach*; ICIMOD: Kathmandu, Nepal, 2012. Available online: https://www.fao.org/fileadmin/user_upload/mountain_partnership/docs/icimod-contribution_of_himalayan_ecosystems_to_water_energy_and_food_security_in_south_asia_a_nexus_appr.pdf (accessed on 15 April 2023).
29. Andrews-Speed, P.; Bleischwitz, R.; Boersma, T.; Johnson, C.; Kemp, G.; VanDeveer, S.D. *The Global Resource Nexus: The Struggles for Land, Energy, Food, Water, and Minerals*; Transatlantic Academy: Washington, DC, USA, 2012.
30. Howells, M.; Hermann, S.; Welsch, M.; Bazilian, M.; Segerström, R.; Alfstad, T.; Gielen, D.; Rogner, H.; Fischer, G.; van Velthuisen, H.; et al. Integrated analysis of climate change, land-use, energy and water strategies. *Nat. Clim. Chang.* **2013**, *3*, 621–626. [[CrossRef](#)]
31. UNECE. *Reconciling Resource Uses in Transboundary Basins: Assessment of the Water-Food-Energy-Ecosystems Nexus*; UNECE: Geneva, Switzerland, 2015.
32. Tidwell, T.L. Nexus between food, energy, water, and forest ecosystems in the USA. *J. Environ. Stud. Sci.* **2016**, *6*, 214–224. [[CrossRef](#)]
33. Hatfield, J.L.; Sauer, T.J.; Cruse, R.M. Chapter One—Soil: The Forgotten Piece of the Water, Food, Energy Nexus. In *Advances in Agronomy*; Sparks, D.L., Ed.; Academic Press: Cambridge, MA, USA, 2017; Volume 143, pp. 1–46.
34. Demiris, G.; Oliver, D.P.; Washington, K.T. Chapter 3—Defining and Analyzing the Problem. In *Behavioral Intervention Research in Hospice and Palliative Care*; Demiris, G., Oliver, D.P., Washington, K.T., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 27–39, ISBN 978-0-12-814449-7.
35. Middleton, C.; Allouche, J.; Gyawali, D.; Allen, S. The rise and implications of the water-energy-food nexus in Southeast Asia through an environmental justice lens. *Water Altern.* **2015**, *8*, 627–654.
36. Endo, A.; Burnett, K.; Orencio, P.M.; Kumazawa, T.; Wada, C.A.; Ishii, A.; Tsurita, I.; Taniguchi, M. Methods of the water-energy-food nexus. *Water* **2015**, *7*, 5806–5830. [[CrossRef](#)]
37. Allouche, J.; Middleton, C.; Gyawali, D. *The Water–Food–Energy Nexus: Power, Politics, and Justice*, 1st ed.; Routledge: Oxfordshire, UK, 2019.
38. Mitchell, B.; Bellette, K.; Richardson, S. ‘Integrated’ approaches to water and natural resources management in South Australia. *Int. J. Water Resour. Dev.* **2015**, *31*, 718–731. [[CrossRef](#)]
39. Mabrey, D.; Vittorio, M. Moving from theory to practice in the water–energy–food nexus: An evaluation of existing models and frameworks. *Water-Energy Nexus* **2018**, *1*, 17–25.
40. Melo, F.P.L.; Parry, L.; Brancalion, P.H.S.; Pinto, S.R.R.; Freitas, J.; Manhães, A.P.; Meli, P.; Ganade, G.; Chazdon, R.L. Adding forests to the water–energy–food nexus. *Nat. Sustain.* **2021**, *4*, 85–92. [[CrossRef](#)]
41. Yue, Q.; Guo, P. Managing agricultural water-energy-food-environment nexus considering water footprint and carbon footprint under uncertainty. *Agric. Water Manag.* **2021**, *252*, 106899. [[CrossRef](#)]
42. Mirzaei, A.; Abdeshahi, A.; Azarm, H.; Naghavi, S. New design of water-energy-food-environment nexus for sustainable agricultural management. *Stoch. Environ. Res. Risk Assess.* **2021**, *9*, 1861–1874. [[CrossRef](#)]
43. Correa-Cano, M.E.; Salmoral, G.; Rey, D.; Knox, J.W.; Graves, A.; Melo, O.; Foster, W.; Naranjo, L.; Zegarra, E.; Johnson, C.; et al. A novel modelling toolkit for unpacking the Water-Energy-Food-Environment (WEFE) nexus of agricultural development. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112182. [[CrossRef](#)]
44. Hatfield, J.L. Soil degradation, land use, and sustainability. In *Convergence of Food Security, Energy Security and Sustainable Agriculture*; Springer: Berlin/Heidelberg, Germany, 2014; pp. 61–74.
45. Karnib, A. Water-Energy-Food Nexus: A Coupled Simulation and Optimization Framework. *J. Geosci. Environ. Prot.* **2017**, *05*, 84–98. [[CrossRef](#)]
46. Bellezoni, R.A.; Sharma, D.; Villela, A.A.; Junior, A.O.P. Water-energy-food nexus of sugarcane ethanol production in the state of Goiás, Brazil: An analysis with regional input-output matrix. *Biomass Bioenergy* **2018**, *115*, 108–119. [[CrossRef](#)]
47. Karamian, F.; Mirakzadeh, A.A.; Azari, A. The water-energy-food nexus in farming: Managerial insights for a more efficient consumption of agricultural inputs. *Sustain. Prod. Consum.* **2021**, *27*, 1357–1371. [[CrossRef](#)]
48. Chai, J.; Shi, H.; Lu, Q.; Hu, Y. Quantifying and predicting the Water-Energy-Food-Economy-Society-Environment Nexus based on Bayesian networks—A case study of China. *J. Clean. Prod.* **2020**, *256*, 120266. [[CrossRef](#)]
49. Zhang, T.; Tan, Q.; Yu, X.; Zhang, S. Synergy assessment and optimization for water-energy-food nexus: Modeling and application. *Renew. Sustain. Energy Rev.* **2020**, *134*, 110059. [[CrossRef](#)]
50. Nhamo, L.; Ndlela, B.; Mpandeli, S. The Water-Energy-Food Nexus as an Adaptation Strategy for Achieving Sustainable Livelihoods at a Local Level. *Sustainability* **2020**, *12*, 8582. [[CrossRef](#)]
51. Xu, Z.; Chen, X.; Liu, J.; Zhang, Y.; Chau, S.; Bhattarai, N.; Wang, Y.; Li, Y.; Connor, T.; Li, Y. Impacts of irrigated agriculture on food–energy–water–CO₂ nexus across metacoupled systems. *Nat. Commun.* **2020**, *11*, 5837. [[CrossRef](#)] [[PubMed](#)]
52. Higgins, C.W.; Najm, M.A. An organizing principle for the water-energy-food nexus. *Sustainability* **2020**, *12*, 8135. [[CrossRef](#)]
53. Kahil, T.; Albiac, J.; Fischer, G.; Strokal, M.; Tramberend, S.; Greve, P.; Tang, T.; Burek, P.; Burtscher, R.; Wada, Y. A nexus modeling framework for assessing water scarcity solutions. *Curr. Opin. Environ. Sustain.* **2019**, *40*, 72–80. [[CrossRef](#)]

54. Rezaei Kalvani, S.; Celico, F. The Water–Energy–Food Nexus in European Countries: A Review and Future Perspectives. *Sustainability* **2023**, *15*, 4960. [CrossRef]
55. Fumagalli, M. The ‘Food-Energy-Water’Nexus in Central Asia: Regional Implications of and the International Response to the Crises in Tajikistan. 2008. Available online: <https://aei.pitt.edu/11082/> (accessed on 3 February 2024).
56. Medarac, H.; Magagna, D.; Hidalgo Gonzalez, I. Projected fresh water use from the European energy sector. In *Disaggregated Fresh Water Withdrawal and Consumption in the EU up to 2050*; European Commission: Brussels, Belgium, 2018.
57. Milne, A. An economic narrative for better managing the European energy crisis. *SSRN* **2022**, *14*, 1–14. [CrossRef]
58. Tirado, M.C.; Hunnes, D.; Cohen, M.J.; Lartey, A. Climate change and nutrition in Africa. *J. Hunger Environ. Nutr.* **2015**, *10*, 22–46. [CrossRef]
59. Rasul, G.; Sharma, B. The nexus approach to water–energy–food security: An option for adaptation to climate change. *Clim. Policy* **2016**, *16*, 682–702. [CrossRef]
60. Todaro, V.; D’Oria, M.; Secci, D.; Zanini, A.; Tanda, M.G. Climate change over the Mediterranean region: Local temperature and precipitation variations at five pilot sites. *Water* **2022**, *14*, 2499. [CrossRef]
61. Nwaiwu, I. The Effects of Climate Change on Agricultural Sustainability in Southeast Nigeria—Implications for Food Security. *Asian J. Agric. Ext. Econ. Sociol.* **2014**, *3*, 23–36. [CrossRef]
62. Famiglietti, J.S. The Global Groundwater Crisis, *Nature Climate Change*, *4*, 945 EP. 2014. Available online: <https://www.semanticscholar.org/paper/The-global-groundwater-crisis-Famiglietti/1718bb152e12624439b493d756d656e727b14e89> (accessed on 3 February 2024).
63. Bandara, J.S.; Cai, Y. The impact of climate change on food crop productivity, food prices and food security in South Asia. *Econ. Anal. Policy* **2014**, *44*, 451–465. [CrossRef]
64. Berardy, A.; Chester, M. V Climate change vulnerability in the food, energy, and water nexus: Concerns for agricultural production in Arizona and its urban export supply. *Environ. Res. Lett.* **2017**, *12*, 35004. [CrossRef]
65. Liu, Q. Interlinking climate change with water-energy-food nexus and related ecosystem processes in California case studies. *Ecol. Process.* **2016**, *5*, 14. [CrossRef]
66. Pachauri, R.K.; Allen, M.R.; Barros, V.R.; Broome, J.; Cramer, W.; Christ, R.; Church, J.A.; Clarke, L.; Dahe, Q.; Dasgupta, P.; et al. Climate change 2014: Synthesis report. In *Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2014.
67. Yang, Y.C.E.; Wi, S.; Ray, P.A.; Brown, C.M.; Khalil, A.F. The future nexus of the Brahmaputra River Basin: Climate, water, energy and food trajectories. *Glob. Environ. Chang.* **2016**, *37*, 16–30. [CrossRef]
68. Yang, Y.C.E.; Ringler, C.; Brown, C.; Mondal, M.A.H. Modeling the agricultural water–energy–food nexus in the Indus River Basin, Pakistan. *J. Water Resour. Plan. Manag.* **2016**, *142*, 4016062. [CrossRef]
69. Feng, M.; Liu, P.; Li, Z.; Zhang, J.; Liu, D.; Xiong, L. Modeling the nexus across water supply, power generation and environment systems using the system dynamics approach: Hehuang Region, China. *J. Hydrol.* **2016**, *543*, 344–359. [CrossRef]
70. Wang, K.; Liu, J.; Xia, J.; Wang, Z.; Meng, Y.; Chen, H.; Mao, G.; Ye, B. Understanding the impacts of climate change and socio-economic development through food-energy-water nexus: A case study of mekong river delta. *Resour. Conserv. Recycl.* **2021**, *167*, 105390. [CrossRef]
71. Naderi, M.M.; Mirchi, A.; Bavani, A.R.M.; Goharian, E.; Madani, K. System dynamics simulation of regional water supply and demand using a food-energy-water nexus approach: Application to Qazvin Plain, Iran. *J. Environ. Manag.* **2021**, *280*, 111843. [CrossRef]
72. Schull, V.Z.; Daher, B.; Gitau, M.W.; Mehan, S.; Flanagan, D.C. Analyzing FEW nexus modeling tools for water resources decision-making and management applications. *Food Bioprod. Process.* **2020**, *119*, 108–124. [CrossRef]
73. Sušnik, J.; Chew, C.; Domingo, X.; Mereu, S.; Trabucco, A.; Evans, B.; Vamvakieridou-Lyroudia, L.; Savić, D.A.; Laspidou, C.; Brouwer, F. Multi-Stakeholder Development of a Serious Game to Explore the Water-Energy-Food-Land-Climate Nexus: The SIM4NEXUS Approach. *Water* **2018**, *10*, 139. [CrossRef]
74. Ngammuangtueng, P.; Nilsalab, P.; Chomwong, Y.; Wongruang, P. Water-energy-food nexus of local bioeconomy hub and future climate change impact implication. *J. Clean. Prod.* **2023**, *399*, 136543. [CrossRef]
75. Geethalakshmi, V.; Gowtham, R.; Bhuvaneshwari, K.; Kumar, S.M.; Priyanka, S.; Rajavel, M.; Balakrishnan, N. Sustainable land-water-food nexus management: Integrated modelling approach. *J. Agrometeorol.* **2023**, *25*, 61–67. [CrossRef]
76. Ravar, Z.; Zahraie, B.; Sharifinejad, A.; Gozini, H.; Jafari, S. System dynamics modeling for assessment of water–food–energy resources security and nexus in Gavkhuni basin in Iran. *Ecol. Indic.* **2020**, *108*, 105682. [CrossRef]
77. Bakhshianlamouki, E.; Masia, S.; Karimi, P.; van der Zaag, P.; Sušnik, J. Science of the Total Environment A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin, Iran. *Sci. Total Environ.* **2020**, *708*, 134874. [CrossRef] [PubMed]
78. Guan, X.; Mascaro, G. Agricultural and Forest Meteorology Impacts of climate change on the food-water nexus in central Arizona. *Agric. For. Meteorol.* **2023**, *333*, 109413. [CrossRef]
79. Dale, L.L.; Karali, N.; Millstein, D.; Carnall, M.; Vicuña, S.; Borchers, N.; Bustos, E.; O’hagan, J.; Purkey, D.; Heaps, C. An integrated assessment of water-energy and climate change in Sacramento, California: How strong is the nexus? *Clim. Chang.* **2015**, *132*, 223–235. [CrossRef]

80. Nadeem, I. Water-Energy Nexus in the UAE in Relation to Climate Change and Adaptation Policy Scenarios. Ph.D. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2019.
81. Janssen, D.N.G.; Ramos, E.P.; Linderhof, V.; Polman, N.; Laspidou, C.; Fokkinga, D.; de Mesquita e Sousa, D. The Climate, Land, Energy, Water and Food Nexus Challenge in a Land Scarce Country: Innovations in the Netherlands. *Sustainability* **2020**, *12*, 10491. [[CrossRef](#)]
82. Wu, L.; Elshorbagy, A.; Helgason, W. Assessment of agricultural adaptations to climate change from a water-energy-food nexus perspective. *Agric. Water Manag.* **2023**, *284*, 108343. [[CrossRef](#)]
83. Li, M.; Li, H.; Fu, Q.; Liu, D.; Yu, L.; Li, T. Approach for optimizing the water-land-food-energy nexus in agroforestry systems under climate change. *Agric. Syst.* **2021**, *192*, 103201. [[CrossRef](#)]
84. Alp, E.; Köksal, M.A.; Demir, Y.; Başkan, O.; Erdoğan, E.K.; Özcan, Z.; Özcan, C. Evaluation of the Water-Energy-Food Nexus with the Focus on Climate Change in a Semi-arid Watershed, Turkey. In *Proceedings of the WEFTEC 2020*; Water Environment Federation: Alexandria, Virginia, 2020.
85. Nasrollahi, H.; Shirazizadeh, R.; Shirmohammadi, R.; Pourali, O.; Amidpour, M. Unraveling the water-energy-food-environment nexus for climate change adaptation in Iran: Urmia Lake Basin case-study. *Water* **2021**, *13*, 1282. [[CrossRef](#)]
86. Chini, C.M.; Konar, M.; Stillwell, A.S. Direct and indirect urban water footprints of the United States. *Water Resour. Res.* **2017**, *53*, 316–327. [[CrossRef](#)]
87. Schmidt, J.I.; Johnson, B.; Huntington, H.P.; Whitney, E. A framework for assessing food-energy-water security: A FEW case studies from rural Alaska. *Sci. Total Environ.* **2022**, *821*, 153355. [[CrossRef](#)]
88. Owen, A.; Scott, K.; Barrett, J. Identifying critical supply chains and final products: An input-output approach to exploring the energy-water-food nexus. *Appl. Energy* **2018**, *210*, 632–642. [[CrossRef](#)]
89. Gazal, A.A.; Jakrawatana, N.; Silalertruksa, T.; Gheewala, S.H. Water-Energy-Food Nexus Review for Biofuels Assessment. *Int. J. Renew. Energy Dev.* **2022**, *11*, 193–205. [[CrossRef](#)]
90. Siciliano, G.; Rulli, M.C.; D’Odorico, P. European large-scale farmland investments and the land-water-energy-food nexus. *Adv. Water Resour.* **2017**, *110*, 579–590. [[CrossRef](#)]
91. Silalertruksa, T.; Gheewala, S.H. Land-water-energy nexus of sugarcane production in Thailand. *J. Clean. Prod.* **2018**, *182*, 521–528. [[CrossRef](#)]
92. Munaretto, S.; Witmer, M. *Water-Land-Energy-Food-Climate Nexus: Policies and Policy Coherence at European and International Scale: Deliverable 2.1 SIM4NEXUS Project-Horizon 2020-689150*; PBL Netherlands Environmental Assessment Agency: The Hague, The Netherlands, 2017.
93. Hua, E.; Wang, X.; Engel, B.A.; Qian, H.; Sun, S.; Wang, Y. Water competition mechanism of food and energy industries in WEF Nexus: A case study in China. *Agric. Water Manag.* **2021**, *254*, 106941. [[CrossRef](#)]
94. Antonelli, M.; Tamea, S. Food-water security and virtual water trade in the Middle East and North Africa. *Int. J. Water Resour. Dev.* **2015**, *31*, 326–342. [[CrossRef](#)]
95. Yillia, P.T. Water-Energy-Food nexus: Framing the opportunities, challenges and synergies for implementing the SDGs. *Osterr. Wasser Und Abfallwirtsch.* **2016**, *68*, 86–98. [[CrossRef](#)]
96. Oludare Sunday, D.; Victo, N.; Margaret, S.K.; Miracle Nevo, C.; Bwambale, J. *COVID-19 and the water-energy-food nexus in Africa: Evidence from Nigeria, Uganda, and Tanzania*; Wiley: Hoboken, NJ, USA, 2020.
97. Al-Saidi, M.; Hussein, H. The water-energy-food nexus and COVID-19: Towards a systematization of impacts and responses. *Sci. Total Environ.* **2021**, *779*, 146529. [[CrossRef](#)] [[PubMed](#)]
98. Zhao, N.; You, F. Food-energy-water-waste nexus systems optimization for New York State under the COVID-19 pandemic to alleviate health and environmental concerns. *Appl. Energy* **2021**, *282*, 116181. [[CrossRef](#)]
99. Yin, C.; Pereira, P.; Hua, T.; Liu, Y.; Zhu, J.; Zhao, W. Recover the food-energy-water nexus from COVID-19 under Sustainable Development Goals acceleration actions. *Sci. Total Environ.* **2022**, *817*, 153013. [[CrossRef](#)]
100. Calder, R.S.D.; Grady, C.; Jeuland, M.; Kirchhoff, C.J.; Hale, R.L.; Muenich, R.L. COVID-19 Reveals Vulnerabilities of the Food-Energy-Water Nexus to Viral Pandemics. *Environ. Sci. Technol. Lett.* **2021**, *8*, 606–615. [[CrossRef](#)] [[PubMed](#)]
101. Rasul, G.; Neupane, N.; Pasakhala, B.; Gurung, P.; Nepal, A.K.; Sharma, E. Deepening regional cooperation for enhancing water, energy, and food security and addressing COVID-19 challenges in the Hindu Kush Himalayan Region. In *Water Resources and Economic Processes*; Routledge: London, UK, 2020; pp. 139–164, ISBN 0429025017.
102. Naidoo, D.; Liphadzi, S.; Mpandeli, S.; Nhamo, L.; Modi, A.T.; Mabhaudhi, T. Post COVID-19: A Water-Energy-Food Nexus Perspective for South Africa. *Eng. Sustain. Dev. Living Preserv.* In *A Future for the Next Generation to Cherish*; Stagner, J., Ting, D., Eds.; Brown Walker Press: Boca Raton, FL, USA, 2021; p. 295.
103. Tayal, S.; Singh, S. COVID-19 and opportunity for integrated management of water-energy-food resources for urban consumption. *Environ. Resil. Transform. Times COVID-19* **2021**, 135–142. [[CrossRef](#)]
104. Berchin, I.I.; de Andrade, J.B.S.O. GAIA 3.0: Effects of the Coronavirus Disease 2019 (COVID-19) outbreak on sustainable development and future perspectives. *Res. Glob.* **2020**, *2*, 100014. [[CrossRef](#)]
105. Falkenmark, M.; Rockstrom, J.; Rockström, J. *Balancing Water for Humans and Nature: The New Approach in Ecohydrology*; Earthscan: Oxford, UK, 2004; ISBN 1853839264.
106. Liu, G.; Arthur, M.; Viglia, S.; Xue, J.; Meng, F.; Lombardi, G.V. Seafood-energy-water nexus: A study on resource use efficiency and the environmental impact of seafood consumption in China. *J. Clean. Prod.* **2020**, *277*, 124088. [[CrossRef](#)]

107. Gephart, J.A.; Troell, M.; Henriksson, P.J.G.; Beveridge, M.C.M.; Verdegem, M.; Metian, M.; Mateos, L.D.; Deutsch, L. The seafood gap' in the food-water nexus literature—Issues surrounding freshwater use in seafood production chains. *Adv. Water Resour.* **2017**, *110*, 505–514. [[CrossRef](#)]
108. Jaroenkietkajorn, U.; Gheewala, S.H. Interlinkage between water-energy-food for oil palm cultivation in Thailand. *Sustain. Prod. Consum.* **2020**, *22*, 205–217. [[CrossRef](#)]
109. Fabiani, S.; Vanino, S.; Napoli, R.; Nino, P. Water energy food nexus approach for sustainability assessment at farm level: An experience from an intensive agricultural area in central Italy. *Environ. Sci. Policy* **2020**, *104*, 1–12. [[CrossRef](#)]
110. Viccaro, M.; Caniani, D.; Masi, S.; Romano, S.; Cozzi, M. Biofuels or not biofuels? The “Nexus Thinking” in land suitability analysis for energy crops. *Renew. Energy* **2022**, *187*, 1050–1064. [[CrossRef](#)]
111. Vahabzadeh, M.; Afshar, A.; Molajou, A. Framing a novel holistic energy subsystem structure for water-energy-food nexus based on existing literature (basic concepts). *Sci. Rep.* **2023**, *13*, 6289. [[CrossRef](#)] [[PubMed](#)]
112. Sewilam, H.; Kimera, F.; Nasr, P. Water energy food nexus model: An integrated aqua-agriculture system to produce tilapia and sweet basil using desalinated water. *Environ. Sci. Pollut. Res.* **2023**, *30*, 15975–15990. [[CrossRef](#)]
113. Yang, J.; Chang, J.; Konar, M.; Wang, Y.; Yao, J. The grain Food-Energy-Water nexus in China: Benchmarking sustainability with generalized data envelopment analysis. *Sci. Total Environ.* **2023**, *887*, 164128. [[CrossRef](#)] [[PubMed](#)]
114. Gill-Wiehl, A.; Ferrall, I.; Patel, S.; Miles, S.; Wu, J.; Newman, A.; Kammen, D.M. Techno-economic scenario analysis of containerized solar energy for use cases at the food/water/health nexus in Rwanda. *Dev. Eng.* **2023**, *8*, 100110. [[CrossRef](#)]
115. Siyal, A.W.; Gerbens-Leenes, P.W. The water–energy nexus in irrigated agriculture in South Asia: Critical hotspots of irrigation water use, related energy application, and greenhouse gas emissions for wheat, rice, sugarcane, and cotton in Pakistan. *Front. Water* **2022**, *4*, 941722. [[CrossRef](#)]
116. Lazaro, L.L.B.; Giatti, L.L.; Bermann, C.; Giarolla, A.; Ometto, J. Policy and governance dynamics in the water-energy-food-land nexus of biofuels: Proposing a qualitative analysis model. *Renew. Sustain. Energy Rev.* **2021**, *149*, 111384. [[CrossRef](#)]
117. Silalertruksa, T.; Gheewala, S.H. Land–water–energy nexus of biofuels development in emerging economies: A case study of bioethanol policy in Thailand. In *The Role of Bioenergy in the Bioeconomy*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 379–402.
118. Ghani, H.U.; Silalertruksa, T.; Gheewala, S.H. Water-energy-food nexus of bioethanol in Pakistan: A life cycle approach evaluating footprint indicators and energy performance. *Sci. Total Environ.* **2019**, *687*, 867–876. [[CrossRef](#)]
119. Stang, S.; Wang, H.; Gardner, K.H.; Mo, W. Influences of water quality and climate on the water-energy nexus: A spatial comparison of two water systems. *J. Environ. Manag.* **2018**, *218*, 613–621. [[CrossRef](#)] [[PubMed](#)]
120. Ghodsvali, M.; Krishnamurthy, S.; de Vries, B. Review of transdisciplinary approaches to food-water-energy nexus: A guide towards sustainable development. *Environ. Sci. Policy* **2019**, *101*, 266–278. [[CrossRef](#)]
121. Song, G.; Gao, X.; Fullana-i-Palmer, P.; Lv, D.; Zhu, Z.; Wang, Y.; Bayer, L.B. Shift from feeding to sustainably nourishing urban China: A crossing-disciplinary methodology for global environment-food-health nexus. *Sci. Total Environ.* **2019**, *647*, 716–724. [[CrossRef](#)] [[PubMed](#)]
122. Pozza, L.E.; Field, D.J. The science of Soil Security and Food Security. *Soil Secur.* **2020**, *1*, 100002. [[CrossRef](#)]
123. Field, D.J.; Sanderson, T. Distinguishing Between Capability and Condition. In *Global Soil Security*; Field, D.J., Morgan, C.L.S., McBratney, A.B., Eds.; Springer International Publishing: Cham, Switzerland, 2017; pp. 45–52, ISBN 978-3-319-43394-3.
124. Zhou, Y.; Gholizadeh, H.; LaVanchy, G.T.; Hasan, E. Inspecting the Food–Water Nexus in the Ogallala Aquifer Region Using Satellite Remote Sensing Time Series. *Remote Sens.* **2020**, *12*, 2257. [[CrossRef](#)]
125. Alam, S.; Gebremichael, M.; Li, R. Remote sensing-based assessment of the crop, energy and water Nexus in the Central Valley, California. *Remote Sens.* **2019**, *11*, 1701. [[CrossRef](#)]
126. Sanders, K.T.; Masri, S.F. The energy-water agriculture nexus: The past, present and future of holistic resource management via remote sensing technologies. *J. Clean. Prod.* **2016**, *117*, 73–88. [[CrossRef](#)]
127. Koppa, A.; Gebremichael, M. Improving the Applicability of Hydrologic Models for Food–Energy–Water Nexus Studies Using Remote Sensing Data. *Remote Sens.* **2020**, *12*, 599. [[CrossRef](#)]
128. McGrane, S.J.; Acuto, M.; Artioli, F.; Chen, P.; Comber, R.; Cottee, J.; Farr-Wharton, G.; Green, N.; Helfgott, A.; Larcom, S. Scaling the nexus: Towards integrated frameworks for analysing water, energy and food. *Geogr. J.* **2019**, *185*, 419–431. [[CrossRef](#)]
129. Wiegleb, V.; Bruns, A. What is driving the water-energy-food nexus? Discourses, knowledge, and politics of an emerging resource governance concept. *Front. Environ. Sci.* **2018**, *6*, 128. [[CrossRef](#)]
130. Dargin, J.; Daher, B.; Mohtar, R.H. Complexity versus simplicity in water energy food nexus (WEF) assessment tools. *Sci. Total Environ.* **2019**, *650*, 1566–1575. [[CrossRef](#)] [[PubMed](#)]
131. Ramos, E.P.; Kofinas, D.; Sundin, C.; Brouwer, F.; Lapidou, C. Operationalizing the nexus approach: Insights from the sim4nexus project. *Front. Environ. Sci.* **2022**, *10*, 787415. [[CrossRef](#)]
132. Vinca, A.; Riahi, K.; Rowe, A.; Djilali, N. Climate-land-energy-water nexus models across scales: Progress, gaps and best accessibility practices. *Front. Environ. Sci.* **2021**, *9*, 691523. [[CrossRef](#)]
133. Pinardi, R.; Feo, A.; Ruffini, A.; Celico, F. Purpose-Designed Hydrogeological Maps for Wide Interconnected Surface–Groundwater Systems: The Test Example of Parma Alluvial Aquifer and Taro River Basin (Northern Italy). *Hydrology* **2023**, *10*, 127. [[CrossRef](#)]
134. Ducci, L.; Rizzo, P.; Bucci, A.; Pinardi, R.; Monaco, P.; Celico, F. The Challenge Posed by Emerging Environmental Contaminants: An Assessment of the Effectiveness of Phenoxyethanol Biological Removal from Groundwater through Mesocosm Experiments. *Sustainability* **2024**, *16*, 2183. [[CrossRef](#)]

135. Zanini, A.; Petrella, E.; Sanangelantoni, A.M.; Angelo, L.; Ventosi, B.; Viani, L.; Rizzo, P.; Remelli, S.; Bartoli, M.; Bolpagni, R. Groundwater characterization from an ecological and human perspective: An interdisciplinary approach in the Functional Urban Area of Parma, Italy. *Rend. Lincei. Sci. Fis. Nat.* **2019**, *30*, 93–108. [[CrossRef](#)]
136. Feo, A.; Pinardi, R.; Artoni, A.; Celico, F. Three-Dimensional High-Precision Numerical Simulations of Free-Product DNAPL Extraction in Potential Emergency Scenarios: A Test Study in a PCE-Contaminated Alluvial Aquifer (Parma, Northern Italy). *Sustainability* **2023**, *15*, 9166. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.