ANALYSIS OF THE WATER–ENERGY–FOOD NEXUS AND ITS CONTRIBUTION TO ENERGY DEVELOPMENT

GRICELDA HERRERA-FRANCO[1,2], HARRY ALBERTO BOLLMANN[3],
JANAINA CAMILE PASQUAL LOFHAGEN[3] & CARLOS MORA-FRANK[4]
[1]Programa de Pós-graudação em Gestão Urbana, Pontifícia Universidade Católica do Paraná (PUCPR), Brazil
[2]Facultad de Ciencias de la Ingeniería, Universidad Estatal Península de Santa Elena (UPSE), Ecuador
[3]Pontifícia Universidade Católica do Paraná (PUCPR), Brazil
[4]Centro de Investigación y Proyectos Aplicados a las Ciencias de la Tierra (CIPAT),
Escuela Superior Politécnica del Litoral, ESPOL, Ecuador

ABSTRACT

The global energy system is moving towards a sustainable future with new development strategies that reduce the carbon footprint, such as the water–energy–food (WEF) nexus. Several countries have implemented this link to provide energy and food security while maintaining the relationship between socio-economic progress and environmental protection. The WEF nexus with energy development generates new interest in innovation, and it is important to explore the growth of this academic field. The work aims to analyse the scientific development of the WEF nexus during energy intervention processes, through bibliometric review models, for the knowledge of strategies in a bioenergy framework. The methodology consists of: (i) information compilation (Scopus and Web of Science) and software selection; (ii) information review on scientific production, author keywords and countries; and (iii) focus group analysis in a framework of energy development. The results show scientific interest from 2007, with exponential growth from 2016. The literature presents the interest of implementing the WEF nexus in energy processes to reduce environmental pollution, like ethanol in gasoline, biorefineries, sustainable agriculture, hydropower, and renewable energies (solar, wind). This scientific approach is dominated by the USA, China and the United Kingdom in environmental science, energy and engineering areas, accounting for 60% of the production. The study shows that the WEF nexus approach to energy developments creates new prospects for decision-making in socio-economic, political, and environmental progress.

Keywords: WEF nexus, bioenergy, sustainability, bibliometric analysis.

1 INTRODUCTION

Energy sources play an essential role in the socio-economic progress of developed and developing countries. Currently, non-renewable energies such as oil and natural gas are considered a resource that sustains modern society and today's economy (fuel consumption and industrial processes) [1], [2]. These energies cover 33.1% of global consumption, generating economic and social benefits [3]. However, estimates indicate a limited reserve for supply from these resources [4].

Although the oil industry integrates sustainability approaches into its activities, there are problems with energy and environmental issues, such as energy demand growth and climate change [5], [6]. Therefore, global organizations have developed renewable energy sources under the sustainability framework for socio-economic development, strengthening environmental protection, and substituting fossil fuels.

Renewable energies are sustainable methods that use the natural resources of an environment, like the dynamics of water (hydropower), the sun heat (geothermal energy), the wind power (wind energy), and the use of biological sources (bioenergy) [7], [8]. In this case, bioenergy is considered a renewable resource that comes from materials of biological origin, like plants or plant derivatives. Bioenergy is the second-largest commercial source of renewable energy after hydropower and is characterized by high efficiency, cleanliness, and

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convenience in the commercial sector [9]. For example, biomass is considered a distinctive and promising type of green energy that has a single-use and can be converted into a biofuel energy source [10], [11]. This advantage allows biofuels to receive much attention over the last two decades from scientists worldwide, with changes in their pace of development, focus, and international collaboration. In addition, bioenergy has a crucial strategic contribution to new energy and economic challenges, like reducing fossil energy use and socio-economic development [12]. Bioenergy production has two phases for the generation of products (e.g., bioethanol, biodiesel, biogas, butane, dimethylether, methanol, hydrogen, vegetable oil): (i) preparation, related to cultivation, harvesting, collection, and (ii) processing, referred to esterification, fermentation, ficher, and gasification [13].

Studies highlight the importance of strengthening a strategic system with renewable energies, mainly in areas with higher socioeconomic and industrial demand and places with abundant biodiversity [14]. In recent years, the water, energy, and food (WEF) nexus have been promoted through international meetings and convenings as a global research agenda and an emerging sustainable development paradigm [15]. The importance of the WEF nexus arises from the scarcity problems of natural resources like water, energy, food, and resources related to human needs [16], [17]. Therefore, the water–energy nexus relationship was established from the importance of water for energy generation in the water supply processes and wastewater treatment, while the food–water nexus relates to crop irrigation for agricultural activities [18], [19].

WEF nexus strengthens the concept of sustainability in resources and management. However, there are limited policy responses and resource constraints in the processes of industrialisation, trade and consumption, with the implementation of the "planning" and "decision-making" frameworks being strategic [20], [21]. Moreover, the close relationship between the WEF nexus and bioenergy security creates problems in the nexus, directly related to food and water security. For example, biofuels used for transport in a country with a high energy demand create the need to occupy new territories to increase the production of biological material [22]. The importance of the WEF nexus in policies in various sectors (e.g. agriculture, water, energy, climate) determines the trade-off outcomes for society and the environment [23]. According to Mirzabaev et al. [24], studying the bioenergy economy in the WEF nexus framework helps a clear picture of positive synergy opportunities and potential constraints.

The WEF nexus information with bioenergy shows the need to incorporate a general analysis of the findings and scientific contribution that countries around the world contribute to the evolution of this study field. Therefore, bibliometric analysis is a type of research that makes it possible to visualise or represent trends related to scientific development [25]. In addition, bibliometrics has contributed to various fields of research, like medicine [26], industry [27], engineering [28], and the relationship between oil and the environment [29]. These analyses use systematic tools or techniques that make it easier to obtain bibliographic information by searching databases like Scopus and Web of Science (WoS) [30]. Scopus has extensive coverage of scientific disciplines, ease of access and visualisation [31], and WoS provides older research with approximately 1,300 prestigious journal articles [32], and 256 disciplines [33].

This leads us to establish some concerns: How to visualise the intellectual structure and the various fields of WEF nexus in the context of bioenergy? Which scientific approaches and countries are most interested in strengthening the WEF nexus concept in energy development?

The work aims to analyze the scientific development of the WEF nexus in energy intervention processes worldwide through bibliometric review models in the Scopus and

WoS databases to know energy development strategies with expert opinions in the scientific area.

2 METHODOLOGY

This research was developed in three phases (Table 1): (i) information compilation in Scopus and WoS databases and use of software (e.g., VOSviewer and Bibliometrix); (ii) review and analysis of the information, generating graphs of scientific production, author keywords, and countries; and (iii) focus group analysis in a framework of energy development.

Table 1: Methodological outline of the study.

Phase I	**1. Information compilation** - *Database:* Scopus and WoS. - *Research topic:* "water-energy-food" OR "water-food-energy" OR "food-energy-water" OR "WEF nexus" OR "WFE nexus" OR "FEW nexus" AND "biofuel*" OR "bioenergy*" OR "biomass".
	2. Softwares used - *VOSviewer:* integral bibliometric mapping. - *Bibliometrix:* data fusion, data cleansing and reference data.
Phase II	**3. Data analysis** - Scientific production of study field. - Author keywords network. - Keyword Frequency. - Scientific production of countries and authors.
Phase III	**4. Focus group analysis** - Expert opinion in the field, based on the framework of energy development.

2.1 Information gathering and software selection

This work is based on the systematic search and structuring of information related to the WEF nexus in the bioenergy field. The collection considers publications of articles, conference papers, books, book chapters and others included in databases (i.e., Scopus and WoS). The search criteria consider the WEF nexus and similar criteria, intercepting bioenergy with biofuel and biomass criteria. For example, the topic search is "water–energy–food" OR "water–food–energy" OR "food–energy–water" OR "WEF nexus" OR "WFE nexus" OR "FEW nexus" AND "biofuel*" OR "bioenergy*" OR "biomass", searching on titles, abstracts, and keywords. In addition, a data filtering mechanism is included, like inclusion terms that consider all types of documents, sources, languages and subject areas, and exclusion terms that involve removing production from the year 2022 (current year). These conditions grouped 139 Scopus publications and 145 WoS publications.

Once the search criteria and conditions are defined, the information is downloaded in Comma-Separated Values (CSV), BibTex, Plan Text File and Excel format. These formats presented inconsistent records, which necessitated a detailed cleaning of the data, eliminating duplicate and missing files (author name, title) – obtaining 138 documents from Scopus and 145 from WoS.

The study used bibliometric management software for data processing, like Visualisation of Similarity Viewer (VOSviewer) and Bibliometrix. VOSviewer is a freely available computer programme that allows the construction and visualisation of connection maps, like author keywords, and countries [34]. This software generated the author keywords map through data extraction-processing and cleaning the information with thesaurus [35], [36]. On the other hand, Bibliometrix is an RStudio package that allows data processing through specific tools [37]. The present study used RStudio version 4.1.2 and the functions readfile/convert2df. This programme made it possible to merge Scopus and WoS data using specific coding and formats (e.g., BibTex and Plain Text File). The combination of data showed 25 unique Scopus documents, 32 unique WoS documents and 113 in both databases, resulting in a total merger of 170 publications that were used in the analyses.

2.2 Analysis of data

This section generates the analysis of the obtained information containing the intellectual approach and its links, considering the scientific production, author keywords network, keywords frequency, and countries–authors relationship. In a first analysis, the scientific output shows the quantitative distribution of publications generated over time. Subsequently, the graph of author keywords allows us to visualise the lines of research in this study field, while the frequency of keywords shows the initial and final evolution. Finally, the last analysis presents the nations and authors who developed this field of research considerably.

2.3 Focus group analysis

The focus group analysis shares scientific opinion content from expert authors in the field, providing a scientific content of quantitative context for the social and academic community [38]. In general, this analysis values the interaction of participants, presenting tactics or strategies to solve problems and transform realities [39].

3 RESULTS

3.1 Analysis of data

3.1.1 Scientific production of the study field

Publications related to the WEF nexus in the bioenergy field is a topic of recent integration in the academic world. Fig. 1 shows that the production started in 2007 with only one publication, maintaining a linear growth until 2014. According to Price's Law [40], the trend becomes exponential from that year onwards. This increase indicates the interest of scientists in integrating the WEF nexus during energy development (in this case, bioenergy), as the topic of friendly energies becomes an important sustainable mechanism in energy generation and multiple water use activities.

3.1.2 Countries–authors relationship

The analysis shows the intersection between the authors and countries, allowing us to know the intellectual contribution. The author keywords are also added to determine their lines of research (Fig. 2). In general, 48 countries and 693 authors have conducted WEF nexus studies related to the bioenergy field, led by the USA, Malaysia, Brazil, and China. USA presents a contribution of 135 publications with six relevant authors in 12 important scientific lines, obtaining prominent participation with the WEF nexus and bioenergy. Although Malaysia is ranked second with 73 contributions, it shows lower participation than other nations, as it has a contribution in six keywords. However, its five principal authors have an outstanding

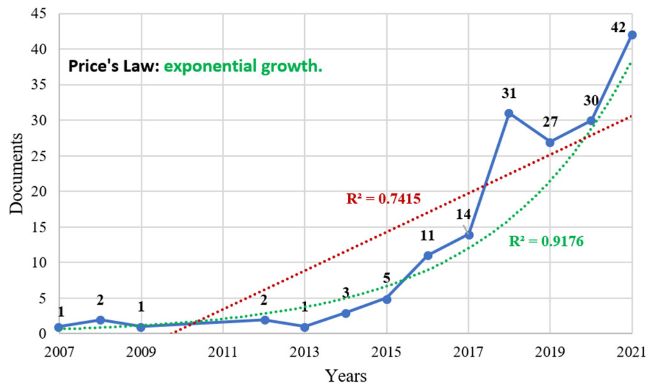

Figure 1: WEF nexus scientific output in the bioenergy field.

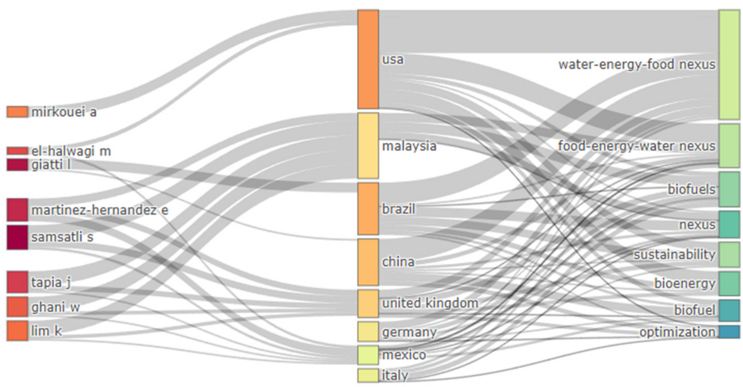

Figure 2: Author–country relationship and lines of research in scientific production.

scientific performance. Brazil and China reflect a close production (61 and 57 papers, respectively) with essential authors in this field of research, such as L. Zhang and L. Giatti. Other countries also contribute to scientific development, like the United Kingdom, Germany, Mexico, and Italy.

3.1.3 Author keywords network

The VOSviewer programme allowed the construction and visualisation of this map by processing 518 keywords. In addition, the cleaning mechanism (thesaurus) and the occurrence conditions (at least four times) presented a total of 26 keywords (nodes), constituting six clusters on the map (Fig. 3).

Cluster 1: "Sustainability and biomass" (red colour), has the highest number of nodes (seven) with 78 occurrences. This cluster shows the outstanding involvement of the food–energy–water (FEW) nexus in biomass relations, sustainability, and its optimisation in these concepts. The information shows the importance of sustainability in the nexus with the framework of socio-economic and environmental activities [41]. In addition, life cycle assessment (LCA) strengthens environmental impact analyses, considering the FEW nexus in energy crop production [42].

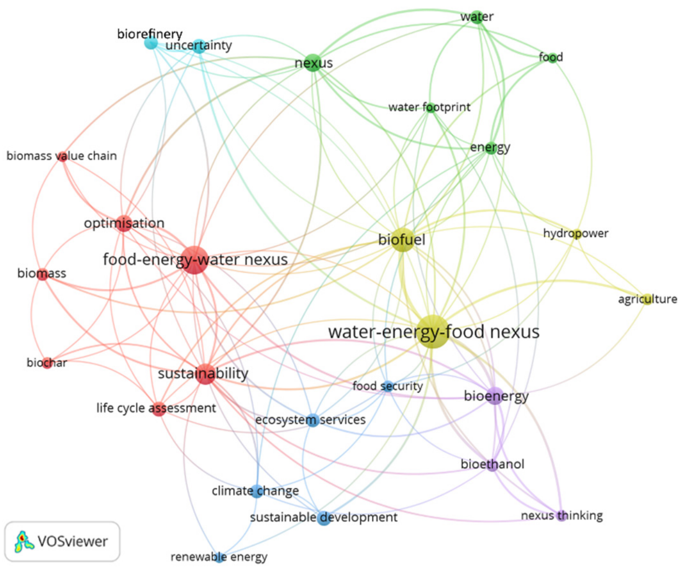

Figure 3: Author keywords connection map.

Cluster 2: “Nexus and water footprint” (green colour), has five nodes totalling 32 occurrences. The cluster shows a distribution of the WEF nexus linked to the water footprint and slightly to food security for multiple water use and energy generation analyses [43].

Cluster 3: “Security and climate change” (blue colour) indicates the connection of five nodes and 31 occurrences in total. In this cluster, food security has a higher magnitude and a solid link to the various types of bioenergy (biofuel and bioethanol), as climate change issues indicate the importance of integrating new sustainability scopes (e.g., WEF nexus and renewable energies).

Cluster 4: “Biofuels” (yellow colour), is representing a set of four nodes (69 occurrences). This cluster indicates the critical contribution of the WEF nexus in using biofuels, as despite containing bio-products (biomass), it generates environmental impacts on food sources and economic capital [44]. In addition, studies highlight that biomass is a viable option for a climate-friendly and energy-efficient economy [45].

Cluster 5: “Bioenergy and nexus integration” (purple colour), has three nodes totalling 22 occurrences. The cluster terms show studies that analyse energy production and its association with bio-products to understand the integration of the WEF nexus in the development of this field [46].

Cluster 6: “Control and bioprocesses” (light blue), has the lowest number of nodes (two) with a total of 15 occurrences. The cluster contains studies indicating biorefineries’ importance in obtaining biofuels to cover the bioenergy demand. However, other studies confirm the environmental problems of biorefineries in hydrographic systems [47].

3.1.4 Keywords frequency

This section shows the keywords that appear in at least three studies, placing the node in the year of highest frequency (Fig. 4) [48]. The data shows that the hydropower power generation industries dominated this field in relationship with other methods, with the highest number of hydropower studies in 2013. In later years, energy production shifted with great interest towards renewable energies and biofuels, as the issue of climate change caused ecosystemic consequences like a lack of water resources for agricultural irrigation and multiple water use. The nexus concepts, sustainability and LCA, are also beginning to be involved in coherence with bioenergy growth to strengthen environmental control during the processes and use of these energies. This relationship arises from the contamination of ecosystems caused by biorefineries and the emission of toxic gases generated by biofuels due to the lack of control during blending with bio-products (low percentage). Finally, the information reflects current relevant topics (2020–2021), like food waste, integrated assessment modelling, nexus thinking, and bioethanol.

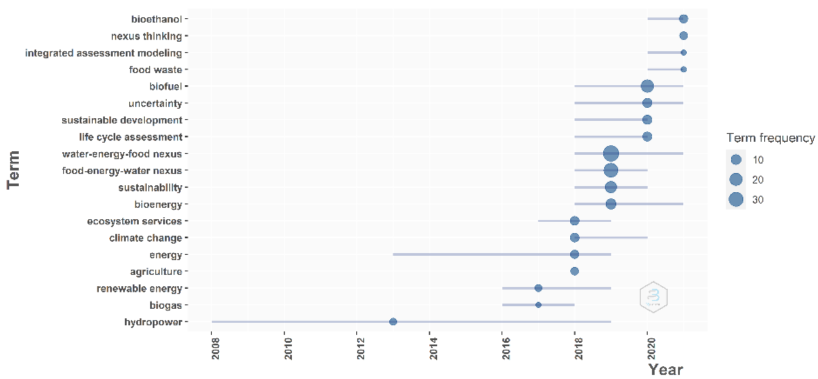

Figure 4: Evolution of the main keywords over time.

3.2 Analysis focus group

Although this scientific field is of recent interest, the information gathered shows the importance of including the WEF nexus in current energy development topics. This relationship strengthens the concept of sustainability in socio-economic activities and environmental protection in a framework of water and food demand due to global population growth. However, this criterion does not show significant results in nations worldwide, mainly developing countries. Therefore, experts consider it essential to implement energy and socio-economic development strategies, like (i) the use of renewable energies available in the natural environment of a locality (solar, wind and water energy), (ii) rescue of water ancestral knowledge, (iii) wastewater use with the implementation of tertiary treatment systems in a context of monitoring and control for water reuse, (iv) natural areas of protection mangrove and bird, known as green dots, (v) enhancing waste management like reuse, composting, biogas, and mechanical treatment.

4 DISCUSSION

The Scopus and WoS databases allowed the information download through a search strategy for data fusion and generation of analyses. However, the authors consider it necessary to clean up the records, as there are inconsistencies in the download, like duplicates and records without author or title information. This cleaning process presents quality and reliable results to understand better the scientific output that addresses WEF nexus studies in energy development. Some publications use Scopus and WoS tools for filtering and subsequent data cleaning, allowing the development of a complete content review [49].

This bibliometric study indicates the scientific interest in integrating the WEF nexus with bioenergy in the last three years (2019–2021). According to Han et al. [50], the WEF nexus faces challenges in developing the concept in science and policy areas of intervention for economic development. Therefore, our results reflected the essentials of the WEF nexus in energy management and multiple water use related to the water footprint and climate change. Hamidov and Helming [51] indicate a strategic conceptual synthesis of the WEF nexus and that it annually strengthens its operation on sustainability issues.

On the other hand, it is essential to mention the strategies found in this study related to the WEF nexus in the development of bioenergy, based on the keywords frequency and author keywords network: (i) the promotion of including life cycle assessment in environmental impact analyses and the WEF nexus in socio-economic development, generates a fundamental relationship in the promotion and monitoring of bioenergy; (ii) food security must have a direct link to the WEF nexus concept, as water use is currently not sustainably managed; (iii) sustainable projects related to climate change should be developed and implemented in developing countries, integrating the direct collaboration of international experts; (iv) the implementation and promotion of biofuels is an affordable way forward for emerging countries; (v) countries with a demand for water, energy and food develop a legal link with global organisations for strengthening the WEF nexus in energy development (e.g. bioenergy); (vi) the sustainable development goals (SDGs) should be integrated more frequently into studies in this field of research.

5 CONCLUSIONS

The scientific production analysis of the WEF nexus with bioenergies shows a recent interest of 14 years (2007–2021) with 170 publications when merging information from Scopus and WoS, and an exponential growth reflected in the last four years (76.4% between 2018–2021). In addition, we highlight the collaboration of 48 countries in various studies, led by the USA and Malaysia. There are also a general 518 keywords, interpreting the central nodes of each cluster that focus on topics like sustainability, biomass, nexus connection and integration, security, climate change, bioprocesses, and bioenergy.

The WEF nexus is an important concept that needs to be integrated more frequently into the energy development of the world's countries, maintaining the link to sustainability. This relationship becomes a fundamental topic in decision-making processes for sustaining the energy–water nexus demand in agricultural systems, municipal and economic environments. On the other hand, the strategies implemented would reinforce this context within an environmental protection and social development framework, highlighting that the themes of current interest are food waste, integrated assessment modelling, nexus thinking, and bioethanol. In addition, the promotion of new sustainable methods such as LCA and the SDGs are crucial in linking them to the WEF nexus and bioenergies.

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