Energy-Water-Food-Environment Nexus and Circular Economy: A Systematic Review

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Abstract. The increasing demand for essential resources such as water, food, and energy will hurt the environment. Nexus thinking emerges as a way of thinking about the interdependence of multiple resource flows within a specific temporal and spatial context, such as energy, water, and food flows in a region. The nexus approach is a type of systems thinking that focuses on natural resource interdependence and how that interdependence can be managed and steered into more integrated and sustainable configurations. The goals of this paper are to systematically review existing research on the energy-water-food-environment nexus and circular economy implementation globally published in the last five years (2019 – 2023) and to identify future research needs in the context of Indonesia. The Scopus database was used in this study. Microsoft Excel and VOS viewer software were applied for the bibliometric analysis. Almost all of the articles reviewed in this study were taken place in other countries. Energy, water, and food security as well as environmental sustainability have become major challenges in Indonesia. Therefore, research regarding the energy-water-food-environment nexus and circular economy to support the SDGs for Indonesia context is required in the future.

1 Introduction

Water and energy are life-sustaining resources that contribute to both economic and social development [1, 2]. Energy and water are inseparably connected, because water requires energy and energy requires water indefinitely. Energy is used to treat and supply water, even though almost all energy production processes require substantial quantities of water. Water and energy have become dependent on each other. This connection has far-reaching consequences for human life, well-being, and economic development [1].

The sustainable development goals (SDGs) agenda includes 17 goals distributed across four pillars of sustainable development, i.e., social development, economic development, environmental development, and law and governance. SDG 6 is “Ensure availability and sustainable management of water and sanitation for all”, and SDG 7 is “Ensure access to affordable, reliable, sustainable and modern energy for all” [3]. These two SDGs are related to energy and water, which are inseparably connected.

In energy production, for example, hydroelectric power demonstrates the importance of water in energy production and implementation. Energy, on the other hand, is required to transport water to communities, produce clean potable water and wastewater, and collect water. Water is needed in the fuel and energy manufacturing sectors for appropriate cooling, discharge, refining, processing, and other activities. Flow variations and groundwater tables have an important influence on the amount of energy produced by dams [1]. The extraction of fossil fuels and biofuel processing require water. Similarly, desalinisation and wastewater treatment also need energy.

On the other hand, population growth as a driver of socioeconomic development has resulted in increased usage of natural resources including energy, water, and food [4]–[7]. In recent years, the energy and water resources usage has increased significantly. Water usage has an impact on energy, food, industrial output, and environmental quality. Since energy is used to treat and distribute freshwater, approximately 8% of global energy is used for water production and 15% of global water is used for energy [8]. In exchange, water is used to cool thermal power plants. Water is required for activities such as petroleum processing, farming, and electricity generation. Energy and water demand have increased globally over the years due to population and economic growth. This progress has made humans more vulnerable to the effects of climate change.

This condition will cause some constraints that seriously impede our ability to meet the goals of sustainable development. Moreover, the natural, social, and economic networks are all intertwined with the energy-water-food-environment. Therefore, the

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multidisciplinary concept of sustainable development requires the integration of energy, water, food, and environmental systems [9].

The circular economy (CE) is a new approach to sustainable management that employs the management of reduction, reuse, recycling, and recovery [10], [11]. This approach increases economic benefits while decreasing the strain on natural resources. The circular economy (CE) has been suggested as a successful model for sustainable water management [12].

This paper aims to systematically examine the existing research on the energy-water-food-environment nexus and the application of circular economy globally published in the last five years (2019 – 2023), and to find further research that needs to be conducted in the future, in the context of Indonesia.

2 Literature Screening and Inclusion

The Scopus database was used in this study to conduct a review of the energy-water-food-environmental nexus and the implementation of a circular economy (CE). A meticulous search strategy was devised, incorporating relevant keywords such as "water”, “energy”,” nexus", “food”, “environment”, and "circular economy". The articles chosen for this study are only from open sources. Furthermore, the keywords of the articles were identified using the Microsoft Excel and VOS viewer software tools in this study.

The following eligibility measures were used to guide the article's screening and inclusion in this literature review study:

1) only English articles were chosen from the peer-reviewed publications that were screened;
2) articles had to concisely explain the nexus principle, emphasizing the links among water, energy, food, environment, and circular economy;
3) articles had to include either a nexus case report or an overview of the nexus approach and circular economy;
4) articles were published within the last five years, in 2019 – 2023, and
5) access to the full text of the articles was required; thus, open-access sources were chosen for this study.

The selected articles were then imported to Mendeley's reference manager. For data extraction and analysis, the keywords of the articles in this study were identified using the VOS viewer software tool that analysed the data from the downloaded Scopus database saved in a Microsoft Excel CSV (comma-separated value) file.

3 Results and Discussion

3.1. Analysis of Bibliometric Network

The VOS viewer software was applied to analyse and visualize the relationships between articles. After choosing one of the similar words like "circular economy" and "CE," or "water-energy nexus" and "WEN," there were 633 open access articles about the energy-water-food-environment-nexus and circular economy discovered in the Scopus database with no year restriction. The database of 633 articles in Microsoft Excel CSV format was further imported into VOS Viewer. The VOS Viewer clustered the keywords into 6 clusters that contain 44 keywords.

Fig 1 illustrates how the 44 words that appeared the most frequently in the articles were linked. According to the bibliometric network analysis, the top keywords used were sustainability, water-energy nexus, climate change, renewable energy, food security, and circular economy respectively. Based on the eligibility criteria used for article screening and inclusion in this study, 57 articles were selected.

3.2. Articles Analysis

Out of the 57 articles reviewed, 40 (70%) discussed the water-energy-nexus or energy-water-food nexus in the context of sustainability, while 17 (30%) focused on the circular economy of water, energy, and wastewater. Among the 38 articles, only 2 of them discussed about energy-water-food-environment nexus.

In addition, the number of articles in the Scopus database about the water-energy nexus or energy-water-food-nexus and circular economy has increased significantly between 2019 and 2023.

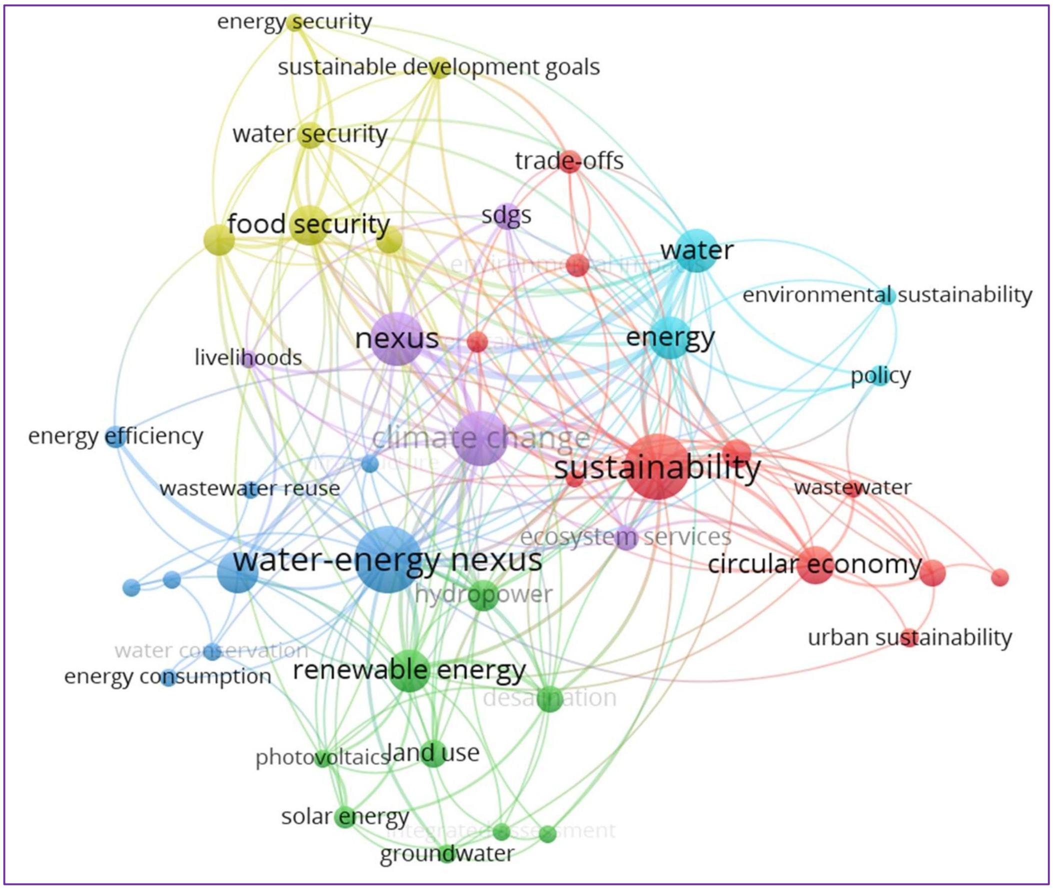

Fig. 1. The bibliometric network analysis of keywords for energy-water-food-environment nexus and circular economy (source: result analysis using VOS viewer software conducted by the authors).

3.3. Energy-Water-Food Nexus

Energy, water, and food are the three vital resources for the survival of humans., and they are critical for achieving long-term global economic development [8], [9], [13]–[16]. Moreover, energy is required for water treatment and distribution, food production, and the development of modernized agriculture. Water, on the other hand, is used to cultivate food crops, for industrial and residential purposes, and to generate energy. Water is also essential in fuel manufacturing, power generation, and processing [13]. Thermal power generation is a water-intensive process, and water is essential throughout the process, from fuel extraction to power generation. If thermal power plants continue to use water at their current rates and present water-related laws remain the same, water withdrawal in India is expected to increase 4.3 times while usage will increase 3.2 times by 2050 [18]. As a result, the water and energy sectors are inextricably linked and interdependent [19]–[22].

Water competition, according to Yaxin [23], is a critical subject in the research of the energy-water-food nexus, that could have an impact on energy, water, and food security, as well as pose substantial challenges in water resource management. The findings from a study conducted by Yaxin [23] revealed that water competition between sectors was extremely intricate and could change dynamically depending on the scenario. A rise in hydroelectric power and flow to the ocean, for example, could result in a reduction in irrigation water supply, but a rise in water for irrigation did not always result in a decrease in hydropower and flow to the sea [23].

Furthermore, sustainability solutions in a region involving multifaceted resource systems, such as the energy, water, and food nexus, are becoming progressively important. According to Covarrubias [24], silo-thinking in natural resource management refers to one-dimensional and sectorial decision-making in which the involved actors do not consider cross-sectorial linkages or interrelationships between different scales in natural resource management. It stifles information exchange and collaboration on synergies and trade-offs between different resource systems, such as water, energy, and food, which are frequently viewed as separate and independent sectors [24].

Sectoral silos are no longer appropriate ways for tackling the challenges in sustainability in the world we live in, because solutions based solely on one sector inevitably impact others, whether by design or by mistake. Such interconnectedness is especially visible and important in the water-energy sectors, as individuals are linked to and often reliant on others. Furthermore, the security and sustainability of water-energy resource supply and distribution are becoming progressively uncertain as a result of increasing stresses from population growth, urbanization, climate change, and economic insecurity [20–22].

The nexus concept is the most recent attempt to advance a cross-sector agenda focused on the essentials of energy, food, and water. Nexus thinking is about breaking down silos; it arises as a way of thinking about the interdependence of numerous resource flows within a specific temporal and spatial context, such as the flows of energy, water, and food in a region or city. The approach of nexus is a type of systems thinking that focuses on the interdependence of natural resources and how that interdependence is or could be managed and steered into more integrated and sustainable configurations [24], [28].

In recent decades, a new term recognised as the energy, food, and water nexus has emerged as a result of strong relationships among energy, water, and food resources [29]. Limitations on these resources, combined with climate change, population growth, and fluctuations in socioeconomic aspects of societies, pose a variety of challenges to the water, food, and energy sectors worldwide. Trade-offs among energy, water, and food subsystems are unavoidable, as are synergies under different policies and/or decisions. To ensure its long-term viability, policymakers should recognize the interactions and trade-offs between different sources of water, food, and energy.

Moreover, the concept of energy and water nexus was developed to foster a more comprehensive strategy for utilizing natural resources [30], [31]. The majority of the focus has been on discovering potential interactions and trade-offs between the various sectors that could be focused on with enhanced technology and management [30].

Because of the increasing global need for water and, energy, as well as the pressures of climate change on these resources, the energy and water nexus has been extensively discoursed both in the policy arena and in the scientific literature [32]. Moving the focus from one specific sector to the intricate connections between them is thought to be critical for the security and sustainability of human society. Cities and regions require a large number of commodities as well as resources to guarantee energy, water, and food sources, which might culminate in substantial greenhouse gas (GHG) releases, solid waste, and pollutants. Encouraging initiatives dealing with water, energy, and food subjects would thus be extremely beneficial to the sustainability of regions or cities [33].

According to Niet et. al [34], recent efforts have begun to integrate energy planning with land and water use planning to address the 'nexus' between these various sectors and their climate and environmental impacts. These integrated modelling structures deal with a number of the links between the water and energy sectors, allowing for more informed decisions. A nexus modelling study for the city of New York, for example, discovered that many energy-saving strategies increased water use and vice versa [34]. The "nexus reasoning" or “nexus thinking” and its multi-sector approach that aims to maximize synergies and diminish trade-offs among its components to improve natural resource management across sectors are critical in responding to the challenge of sustainability for efficient utilisation of resources by the SDGs [35], [36]. The nexus approach is considered a new sustainability framework for coping with limited resources. Moreover, the energy-water-food nexus approach promotes multilevel and inter-sectoral governance, assisting in addressing the inefficiencies and complexities in achieving the SDGs [37].

3.4. Energy-Water-Food-Environment Nexus

Yazdandoost [38] reported that the growing demand for essential resources such as water and energy will damage the environment. As a consequence of this, the optimization of energy and water portfolios has been extensively researched to ensure environmental sustainability while also taking constraints into account.

Furthermore, long-term solutions to overcome water scarcity and energy demand management are required to manage and regulate climate change and man-made stresses. Simultaneously, the energy and water nexus should be taken into account locally and regionally in policy-making to maximize environmental benefit [38]. Yazdandoost [38] reported that a new effective strategy constructed on the energy-water nexus has been established to identify optimally suited locations for implementing desalination using wind energy and solar energy in Texas. To deal with water and energy shortages, uncertainties, and unreliability, the framework of projected approaches should be reviewed in various sectors, resulting in both short-term and long-term solutions capable of meeting unfulfilled needs in both the energy and water sectors.

Yazdandoost [38] devised a comprehensive portfolio-based approach to the energy-water-environment nexus, as shown in the schematic illustration in Fig. 2.

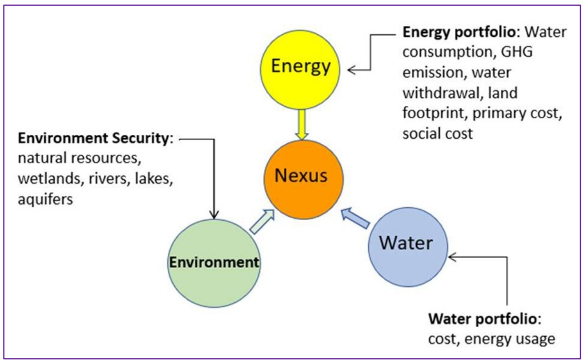

Fig. 2. The schematic of water-energy-environment nexus [38].

Another study conducted by Nasrollahi [39] argued that the principle of sustainable development has been adopted as a policy goal to safeguard the next generation, and the connection between the water, energy, food, and environment sectors has been identified as the nexus approach in the establishment of integrated strategies. In a study conducted in the Urmia Lake basin (Iran), Nasrollahi [39] used two models to simulate energy, water, food, and environmental fluctuations over 20 years: WEAP (Stockholm Environmental Institute, Stockholm, Sweden) and LEAP (Stockholm Environmental Institute, Boston, MA, USA). Using a multi-criteria decision analysis approach, nine policy scenarios and two climate scenarios were put together to assess sustainable development. Results showed that sustainable development will be achieved by taking challenging targets in the energy, potable water, agricultural, and industrial sectors in the study area. However, social, technological, and political obstacles are viewed as impediments to achieving the objectives of this scenario. Furthermore, changes in industry structure and growth have the greatest impact on achieving sustainable development.

3.5. Circular Economy in the Context of Energy and Water Sectors

Nexus thinking and circular economy are emerging as promising solutions for resource sustainability. While the nexus approach aims to cut inefficiencies and waste by focusing on resource interdependence, the circular economy intends to minimize waste by reusing, recycling, and recovering materials [40], [41]. A circular economy is a new approach to sustainable management, using the management of reduction, reuse, recycling, and recovery that allow conservation [16], [42]–[44]. The circular economy is built on a new paradigm regarding the connections between customers, markets, and natural resources, to promote sustainable and resource-efficient practices and allow an economy to grow while minimizing the number of essential resources extracted [45], [46]. The circular economy is also widely regarded as a system-level proposal to address problems caused by current usage and production patterns [47]. Moreover, the circular economy is emerging as a regenerative concept that reduces emissions, relies on renewable energy, and eliminates waste by designing closed-loop systems and reusing resources and materials. [48], [49].

The transition to a circular economy will promote more efficient water use, improving society's ability to reconcile the supply-demand imbalance. Tzanakakis et.al [45] reported that according to the findings of an OECD survey on the circular economy in regions and cities, 66% of the surveyed circular economy initiatives discovered water and sanitation as crucial sectors for circular economy application, closely followed by the waste sector (78%). In addition, the effective treatment of waste to be used as a resource in the future is critical to achieving environmental sustainability and moving toward a circular economy [50].

Tzanakakis et.al [45] argued that closing the loop in water use and water management could provide a variety of economic, environmental, and social benefits; reuse can enhance the status of the environment by replacing abstractions, minimizing anthropic pressure, and reducing the pressure of wastewater treatment plant discharges on sensitive areas. Economically, reuse will extend the valuable water life cycle, increase resource productivity, and diminish dependency on primary resources like water, energy, and nutrients (nitrogen and phosphorus) [45].

Example of circular economy in the water sector is water reuse and treated wastewater reuse [42], [51]—treated wastewater reuse benefits agriculture in a variety of ways [51]. Water reuse technology is important in local food production and helps to resolve the water scarcity problem. Wastewater reuse technology, in addition to a substitute for soil irrigation sources, has enormous potential for preserving available groundwater resources. Because wastewater is treated before entering the aquifer, there is little chance of pollution from it. It reduces the pressure in freshwater sources by using 70% of existing effluent for agriculture. Wastewater technology applications help to combat the worldwide challenge of groundwater resource shortage [51].

Abdelzaher et al. [52] carried out a research project to develop a conceptual plan of new technologies in the application of energy-water-food in new cities in Wadi-Dara (Egypt) using a subterranean reservoir to achieve a circular economy for a holistic approach between the energy and water nexus.

The carbon-intensive and energy-intensive wastewater treatment plans might turn into substantial energy manufacturers and recycled metallic and organic substance producers, thus contributing to the circular economy, wide-ranging sustainable development goals, and the energy-water-food-sanitation-carbon nexus [53]. Rani et.al [53] carried out investigations into waste(water)-based energy-extracting innovations, including their engineering performance, environmental benefits, and techno-economic feasibility. The study proposed four critical strategies for achieving energy sufficiency and net-zero carbon in the water sector, including (a) upgrading the development of energy efficiency; (b) energy harvesting from treated sewage; (c) optimizing on-site renewable capacity and improving biogas; (d) an innovative approach to decentralized energy-water supply elements.

A study conducted by Samberger [54] reported that decarbonisation of the energy sector through increased renewables deployment, measures to increase energy efficiency in buildings, a focus on a circular economy, protection of ecosystems and biodiversity, adoption of a greener and healthier agriculture system, and increased adoption of electric vehicles are among the key steps to achieving the SDG objectives.

According to Ghomi et.al [55], creating a circular economy system allows for adequate management of the life cycle of raw materials and enables profitable economic development for society, businesses, and the environment. Furthermore, a circular economy system seeks to put an end to consumerism by conserving elements, products, and substances at their highest advantages and value. In other words, a circular economy system is based on a culture of repairing and recycling and generates energy from renewable sources, whereas a linear economy generates energy from finite resources.

Reusing wastewater for irrigation represents an opportunity to reduce costs associated with fertilizer requirements and rising water demands, especially in water-stressed areas. The resource's high nutrient concentration can be reinjected into agricultural activities, potentially reducing reliance on expensive and energy-intensive commercial fertilizers. This will aid in the transition to a circular model in which resource recovery and recycling are encouraged [56].

Furthermore, the circular economy concept has triggered the development of new innovative technologies/processes for efficient water utilization, the identification of alternative water sources (primarily treated urban wastewater), and the closure of water-related loops to balance water demand and supply [57]. The organic matter, nutrients, cellulose, and biopolymers from wastewater treatment processes could be recovered to create long-lasting biocomposites and energy. Indeed, as the global demand for renewable energy and organic matter grows, organic wastes such as sewage sludge could be one of the available resources. According to Valenti and Toscano [57], because of the importance of developing renewable energy sources, there is growing attention to establishing anaerobic digestion for the production of biomethane, which both offers green energy and diminishes waste disposal treatment. Sewage sludge (SS), a major by-product of wastewater treatment plants (WWTPs), has the potential to be used as a substrate for soil fertilization and remediation, as well as an energy resource for producing electricity and heat using conventional technologies [57].

4 Conclusion

Limitations of energy, water, and food, combined with climate change, population growth, and changes in socioeconomic aspects of societies, pose several challenges to the energy, water, and food sectors around the world. Energy, water, and food subsystem trade-offs are unavoidable, as are synergies under different policies and/or decisions. Moreover, the increasing demand for energy, water and food will hurt the environment. Policymakers must recognize the synergies and trade-offs between various sources of energy, water, and food to ensure their long-term viability. Therefore, it is important to conduct extensive research on the optimization of energy, water and food portfolios to ensure environmental sustainability while also taking constraints into account.

Based on this literature review study, the research regarding energy-water-food-environment nexus and circular economy in the context of Indonesia is very rare. All the articles that were reviewed in this paper are based on research conducted in foreign countries. Food security, energy security, water resources, and environmental sustainability have become major challenges in Indonesia. In the future, some research regarding the energy-water-food-environment nexus and circular economy is necessary to be conducted in Indonesia. The following topics are examples of future research that needs to be conducted in the Indonesia context regarding the energy-water-food-environment nexus and circular economy to support the SDGs:

1) optimisation of energy-water-food nexus for sustainable river basin;
2) application of circular economy in energy production using sewage sludge from wastewater treatment plan;
3) ablution water reuse in mosques as the implementation of a circular economy for water conservation;
4) optimisation of energy-water-food-environment nexus in small islands;
5) wastewater reuse for agriculture to reduce water demand in water-stressed regions; and
6) simulation model for energy-water-food-environment nexus in a river basin.

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