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Sustainable design of water–energy–food nexus: a literature review

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One of the most agreed upon definitions of sustainability states that in order to achieve a sustainable development, the needs of the present must be met without compromising the ability of future generations to meet their own needs. Yet, the accomplishment of this target has its own challenges given the high growth of human population. All human beings require water, energy, and food in order to survive. The aim, then, is to satisfy these requirements through an adequate distribution of resources. The objective of this article is to explore, through a literature review, the application of the concept of sustainable design of the water–energy–food nexus. It is important to design supply chains that are as sustainable as possible while also fulfilling basic human needs.

Sustainability spotlight statement

Sustainability in the water–food–energy nexus is essential to guarantee the responsible and equitable use of natural resources. The growing demand for these resources and the scarcity in some regions of the world make it necessary to address these challenges from an integrated and holistic perspective. The impact of sustainability on the water–food–energy nexus is related to several United Nations Sustainable Development Goals (SDGs), such as SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy) and SDG 12 (Responsible consumption and production). It is also linked to SDG 13 (Climate Action) and SDG 15 (Life on Land). In short, sustainability in this nexus is essential to achieve a fairer and more equitable future for all.

1. Introduction

Water, energy and food are essential for human well-being, poverty reduction and sustainable development. Global projections indicate that demand for freshwater, energy and food will increase significantly over the next decades under the pressure of population growth and mobility, economic development, international trade, urbanization, diversifying diets, cultural and technological changes, and climate change.[1] Water, food and energy form a nexus at the heart of sustainable development. Agriculture is the largest consumer of the world's freshwater resources, and water is used to produce most forms of energy. Demand for all three is increasing rapidly. To withstand current and future pressures, governments must ensure integrated and sustainable management of water, food, and energy to balance the needs of people, nature and the economy. Demand for water, food and energy is increasing. Pressure on the nexus is being driven by a rising global population, rapid urbanization, changing diets and economic growth. There is a significant global move away from a mainly starch-based diet to an increasing demand for more water-intensive meat and dairy as incomes grow in many countries. Food production and energy are highly water intensive.[2] Agriculture is the largest consumer of the world's freshwater resources, and more than one-quarter of the energy used globally is expended on food production and supply. Most of the energy generation is water intensive, such as its use in coal-fired power plants and in nuclear reactors, and in bio-fuel crop production. Pressure on the water–food–energy nexus threatens the Sustainable Development Goals (SDGs). As water becomes scarcer and more stretched, its ability to support progress in several of the SDGs, particularly on poverty, hunger, sustainability, and the environment, is being reduced.[2] Goal 6 of the Sustainable Development Goals explains the relevance of this point:

Goal 6: ensure availability and sustainable management of water and sanitation for all. Sustainable Development Goal 6 goes beyond drinking water, sanitation, and hygiene to also address the quality and sustainability of water resources, critical to the survival of people and the planet. The 2030 Agenda recognizes the centrality of water resources to sustainable development, and the vital role that improved drinking water, sanitation and hygiene play in progress in other areas, including health, education, and poverty reduction.

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Governments must increase renewable energy sources. There needs to be much more support for the development of less water-intensive renewable energy, such as hydropower and wind. Geothermal energy has great potential as a long-term, climate independent resource that produces little or no greenhouse gases and does not consume water.[3] The Sustainable Development Goals, number 7 refers to the importance of this point.

Goal 7: ensure access to affordable, reliable, sustainable, and modern energy for all. Access to affordable, reliable, and sustainable energy is crucial to achieving many of the Sustainable Development Goals – from poverty eradication *via* advancements in health, education, water supply and industrialization to mitigating climate change. Energy access, however, varies widely across countries and the current rate of progress falls short of what will be required to achieve the Goal. Redoubled efforts will be needed, particularly for countries with large energy access deficits and high energy consumption.

Sustainable agriculture is critical. the integrated systems of land, soil and water are being stretched to breaking point. Efficiency measures along the entire agrifood chain can help save water and energy, such as precision irrigation based on information supplied by water providers, and protection of ecosystems alongside agriculture and energy production can ensure environmental integrity. Ecosystems must be valued for their vital services. Governments must harness the power of nature instead of allowing its destruction and degradation in the pursuit of food and energy. 'Green infrastructure', such as land dams to capture runoff in arable fields or planting forests to protect soil and assist groundwater recharge, are some examples of creating a more sustainable water–food–energy nexus and a 'greener' economy. Integrated management of water–food–energy must be a top priority. Because of this nexus' crucial role in many SDGs, decision-makers in all three domains must cooperate on water resource management, ecosystem protection and water supply and sanitation.[3] The goal number 2 of the SDGs impacts on this issue.

Goal 2: end hunger, achieve food security and improved nutrition and promote sustainable agriculture. This goal seeks sustainable solutions to end hunger in all its forms by 2030 and to achieve food security. The aim is to ensure that everyone everywhere has enough good-quality food to lead a healthy life. Achieving this Goal will require better access to food and the widespread promotion of sustainable agriculture. This entails improving the productivity and incomes of small-scale farmers by promoting equal access to land, technology and markets, sustainable food production systems and resilient agricultural practices. It also requires increased investments through international cooperation to bolster the productive capacity of agriculture in developing countries.

In this context, the water–energy–food nexus has emerged as a useful concept to describe and address the complex and interrelated nature of our global resource systems, on which we depend to achieve different social, economic, and environmental goals. In practical terms, it presents a conceptual approach to better understand and systematically analyze the interactions between the natural environment and human activities, and to work towards a more coordinated management and use of natural resources across sectors and scales. This can help us to identify and manage trade-offs and to build synergies through our responses, allowing for more integrated and cost-effective planning, decision-making, implementation, monitoring and evaluation.[4]

2. Water–energy–food nexus problem

There are several fundamental and interconnected problems that threaten human existence and which must be addressed.[5] Most of these problems are closely related to the production, use and distribution of water, energy, and food within in developing countries.[6]

Understanding the complicated relationship that binds the water, energy and food systems is the foundation in the development of a sustainable future.[7] Hague,[8] visualizes the water–energy–food (WEF) relationship as a strong pillar which generates global security, prosperity, and equity. The WEF relationship first attracted attention in 2011 at the Bonn Nexus Conference held at the United Nations Climate Change Colloquium.[9] The now known "Bonn Conference" outlined the need to address sustainability issues in the highly interrelated sectors of WEF security.

The interrelationship of the WEF system goes beyond quantifying the water footprint in food production, estimating CO_2 emissions from water supply chains or analyzing the generation of electricity from new sources.[10] In other words, other elements such as the economical, the environmental and the societal must be considered. At the heart of this interrelationship lies the interdependence of resources which are resource cost (determines the efficiency of production) and resource demand (creates demand for other resources).[11] Food production requires both water and energy. Energy is essential in the irrigation system, in the production of fertilizer, in the raising of livestock and in the entire transformation chain, *i.e.*, distribution, packaging, storage and sale. Water extraction, water transferring, water treatment and water distribution require energy, on the other hand, energy generation requires water.[12] Factors such as increasing urbanization, environmental issues, and economics intensify the interrelationship of the

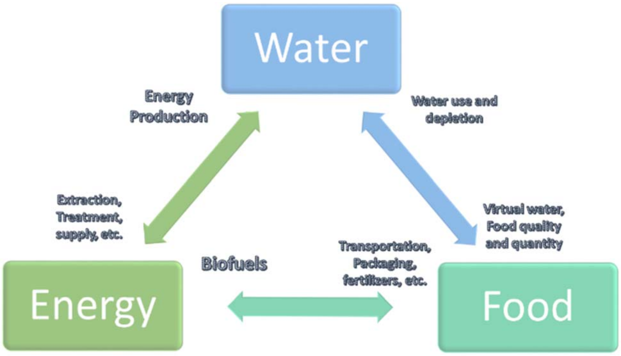

Fig. 1 Interrelationship of the WEF nexus.

WEF nexus. Fig. 1 shows the strong interrelationship of the WEF nexus.

Economic policies can either intensify or mitigate the interrelationship of the WEF nexus. Ignoring the interdependence and such policies will only create a negative impact on the nexus. However, one of the many challenges of the nexus is to efficiently manage the different scales, *i.e.*, the adjustment of resources between localities, regions, and countries.[13] Aspects such as social or environmental security are an important part of the economic development of a region or area, due to the shared nature of energy, water, and the multiple effects that both have on the food sector. By meeting human development needs through the provision of the WEF, it becomes clear that the safeguard of a country, state and region will only increase.[14] The connection of the water–energy–food nexus is greatly influenced by economic policies, which have an impact on a variety of factors. These consist of:

Resource distribution: economic policies govern how limited resources, such as water and land, are distributed across various industries, such as the production of energy, food, and water. Resources may be allocated fairly or with a bias toward particular industries, depending on the policy priorities. Agricultural policy, for instance, may place a higher priority on food production than on effective water and energy usage, or *vice versa*.

Market regulation: markets for food, energy, and water can be regulated by economic policy. Pricing, subsidies, taxes, and other mechanisms that affect resource production, distribution, and consumption are impacted by this legislation. Effective pricing plans for electricity and water, for instance, can encourage efficient use of those resources and the adoption of environmentally friendly technologies.

Investment in technology and infrastructure: economic policies should promote investment in technology and infrastructure for the production of food, energy, and water. For instance, stimulus plans may allot money to build dams, renewable energy facilities, or effective irrigation systems. The availability of resources, sustainable resource management, and food production are all greatly impacted by such investments.

Environmental protection: economic policies can encourage the preservation of natural resources and the protection of the environment. Sustainable practices in water use, energy consumption, and food production are promoted through the implementation of environmental rules, tax incentives, or programs for payment of environmental services. These regulations promote clean technology adoption, resource efficiency, and pollution reduction.

Today, one of the WEF nexus' main problems is the fulfillment of food demand in the face of an ever-growing world population without compromising natural resources and without generating a negative environmental impact.[15] Yet, through the development of sustainable methods of ecological development, a solution can be achieved. These methods must set their focus on developing countries as more than 90% of the world's population growth is generated in these countries, and it is they who are generally prone to water scarcity and malnutrition.[16]

The rising cost of water, energy and food translates into higher costs for goods or services.[17] Thus, the problem of the WEF nexus is the influence of the availability, demand, and costs of each element, as well as other factors that may intervene. The WEF nexus seeks a balance the green economy development model to address the growing challenge of WEF security and its approach to managing this challenge.[18]

2.1 Elements and interactions in the WEF nexus

As mentioned above, the WEF nexus is usually viewed from the perspective of the decision-maker. By adopting the water element approach, the energy and food sectors become users of the source element.[19] From the standpoint of the food element, water and energy are inputs.[20] And from the standpoint of the energy element, water, such as biomass, a biological source, is feedstock. Food is often an output.[21] Regardless of the scenario, the adopted perspective will influence the outcome of the overall nexus. This is driven by the specific priorities of the region, state, or country, as well as the data, resources, and tools available.

The identified elements of the WEF nexus are as follows:[22]

- Limited resources.
- Rapidly growing world demand.
- Population areas without access to WEF (quantity and quality).
- Interaction of supplies, local, regional, national, and/or international trade.
- Variations in supply and demand, in addition to variable availability.
- Dependence on climate change and environmental impacts.
- Social security problems.
- Regulated markets.
- Implications of explicit risks.

Each one of the WEF elements affects every other element involuntarily. Therefore, the interaction is direct, and the effects of ignoring one aspect will have a direct repercussion on the others; thus, a systematic and coordinated plan which will result in the real interaction between water, energy, and food is needed.[17]

3. Sustainability criteria

As aforementioned, the water–food–energy nexus consists of a complex system that comprises the interdependence of water, food, and energy systems. It is important to highlight that these systems are not only interconnected but also dependent on each other. For this reason, any changes in one system could have significant positive or negative impacts on the others. Therefore, understanding the dynamics and interdependence of the water–food–energy nexus is crucial for developing sustainable policies and management practices that can ensure the availability of these resources in the future.

In order to better understand and manage the WEF nexus, several indicators have been developed and applied to evaluate the different aspects of the WEF nexus. These indicators help to measure and monitor the quantity, quality, efficiency, and sustainability of these systems. They provide a quantitative basis for identifying areas where improvements can be made and for tracking progress over time. In this sense, this section provides and explores some indicators used to assess the sustainability of a water–energy–food nexus.[23]

Due to the large number of indicators that exist, the scales they use, and the complexity of analyzing them together, different indicators have been developed. However, a common index used to address these challenges is the water–energy–food nexus index (WEFNI) which was proposed by Juwana *et al.*[24] This index provides information to decision makers about the performance of the WEF nexus in an easy way. It is important to note, that WEFNI is considered a normalization method that helps to analyze different sustainability criteria. Mathematically, WEFNI can be described as follows:

$$X_i = \frac{Y_i^{\max} - Y_i}{Y_i^{\max} - Y_i^{\min}} \tag{1}$$

$$X_i = \frac{Y_i - Y_i^{\min}}{Y_i^{\max} - Y_i^{\max}} \tag{2}$$

$$\text{WEFNI} = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{3}$$

where X_i is the normalized value of indicator i, Y_i represents the current value of indicator i, $Y_i^{\max}$ is the most preferred value of indicator i, whereas $Y_i^{\min}$ represents the least preferred value. w_i is the weight factor applied to indicator i, and n indicates the number of indicators. Please note that there are two equations to determine X_i. The reason is quite simple: eqn (1) is used for indicators where larger values are preferred, whereas eqn (2) is used for indicators where smaller values are preferable. Therefore, it is important to note that based on the normalization, the WEFNI can take values between 0 and 1, where 1 represents the best situation and 0 represents the worst.

As aforementioned, WEFNI allows to evaluate different sustainable indexes, in this sense, diverse authors have reported some of the most common indexes used in a water energy food nexus. The following are examples of some of these common indexes.

3.1 Water footprint

It is important to note that the water footprint not only measures the amount of water used in the production of a product or service, but also the quality of the water used and the environmental impact of water production. Therefore, the assessment of the water footprint should consider not only the quantity of water used, but also the environmental and social context in which the water is used. The water footprint is an indicator that measures the amount of water used in the production of goods or services, including the production of food and energy.[25,26] The water footprint consists of three components:

- Green water footprint: measures the amount of rainwater used in the production of a product or service.
- Blue water footprint: measures the amount of surface or groundwater used in the production of a product or service.
- Gray water footprint: measures the amount of water needed to dilute the pollutants present in the water used in the production of a product or service.

The water footprint is measured in terms of volume of water used, and is typically expressed in cubic meters (m^3). Calculating the water footprint involves identifying all sources of water used in the production of a product or service, and measuring the amount of water used at each source. The water footprint can also include water used in transportation, processing and waste disposal associated with the product or service.[25,26]

The water footprint is used to assess the sustainability of water use in food and energy production, as well as to identify opportunities to reduce water use and improve water use efficiency. By measuring and reducing the water footprint, environmental sustainability and efficiency of the water–energy–food nexus can be improved.[27]

3.2 Carbon footprint

The carbon footprint is an indicator that measures the amount of greenhouse gases (GHG) emitted by the production of goods or services, including food and energy production. The carbon footprint is measured in terms of mass unit of CO_2 equivalent (CO_2e), which is a standardized measure that converts emissions of other greenhouse gases into their equivalent in terms of CO_2.[28,29]

In the context of the water–energy–food nexus, the carbon footprint can be used to assess the environmental sustainability of food and energy production. For example, food production can contribute significantly to GHG emissions due to the intensive use of fertilizers and pesticides, the emission of methane from livestock, and the transport of food along the supply chain.[29,30]

Calculating the carbon footprint can be a complex process and requires accurate and detailed data on the GHG emissions associated with the product or activity in question. There are different methodologies for calculating the carbon footprint, however, a commonly used tool is life cycle analysis.[28,30]

3.3 Energy efficiency

Energy efficiency is an indicator that measures the amount of energy used in the production of goods or services, including the production of food and water, and the efficiency with which this energy is used. It can be measured in terms of energy consumption per unit of output, or as a percentage of the total energy used in production.[31,32] Additionally, the energy efficiency can be an important tool for improving the sustainability and efficiency of the water–energy–food nexus.[32] Improved energy efficiency can reduce the amount of energy needed to produce a product or service, which can reduce production costs and reduce greenhouse gas emissions associated with energy production. To improve energy efficiency in food and water production, various strategies can be implemented, such as adopting more efficient technologies, improving energy management, and reducing energy waste in production processes. It is also important to consider the source of energy used in production, and to promote the use of renewable and clean energies.[31]

In addition to reducing production costs and greenhouse gas emissions, greater energy efficiency can also improve the competitiveness of products and services in the marketplace. Consumers are increasingly aware of the importance of sustainability and energy efficiency, and adopting more efficient production practices can be a competitive advantage for companies.

3.4 Food production efficiency

Food production efficiency is an indicator that measures the amount of food produced per unit of input used. The calculation of food production efficiency can vary according to the type of input used, but in general it involves measuring food production and dividing it by the input used.[33]

For example, food production efficiency can be calculated by dividing the amount of food produced (in terms of weight, volume or monetary value) by the amount of land, water, energy, fertilizer, pesticides or other inputs used in production. This indicator can be expressed in terms of kilograms per hectare (kg ha^{-1}), liters per kilogram (l kg^{-1}), or any other unit that is relevant to the type of input used.[23]

Calculating efficiency in food production can be a complex process that requires accurate data on production and input use. It is also important to consider other factors that can affect the efficiency of food production, such as climate, agricultural practices used, soil quality, and access to technologies and knowledge.

Therefore, the objectives of this paper are to carry out a bibliographical review on the following topics: evaluation of the interdependence between water, energy and food and to understand and analyze the interaction and interrelationships between water, energy and food resources. Analyze current challenges and constraints and investigate the challenges and constraints associated with the sustainable design of the water–energy–food nexus. Identification of opportunities to improve sustainability and evaluate opportunities to improve sustainability in the design and management of the water–energy–food nexus. Establishment of conceptual or methodological frameworks for the sustainable design of the water–energy–food nexus. This may involve integrating sustainability principles into system design and identifying indicators and metrics to assess the sustainability of proposed designs. Environmental and socioeconomic impact assessment of different sustainable design options for the water–energy–food nexus. This may include life cycle assessment, cost benefit analysis, and resilience and equity assessment. Finally, based on the results of the review, propose concrete solutions and recommendations to improve the sustainability of the water–energy–food nexus. These recommendations can be addressed to designers, policy makers, decision makers and other relevant stakeholders.

4. Sustainability of the energy-water-food nexus

Sustainability in the WEF nexus is inherent in the interrelationship between water–energy–food. The interdependence of water resources to those of energy and food, under a scheme of economic, social, and environmental benefits will result in an adequate distribution of elements, thus providing an environment of sustainability. However, the WEF nexus has not always been visualized under the concept of sustainability. In this article we intend to conduct a comprehensive literature review presenting the vision of various authors in the framework of the WEF nexus and sustainability. In this sense, the studies addressed in this work, dating from 2011 up to the present, were utilized in the present research. However, due to the large volume of available works from this period, only a selected number were explored in detail. Even though all of the works examined contribute significantly to advancements in the water–energy–food (WEF) nexus, the ones explored in detail offer innovative solutions in ecological sustainability and progress towards achieving Sustainable Development Goals.

One of the first research works to present a sustainability approach in the WEF nexus was written by Bazilian *et al.*[22] in 2011. In their work, Bazilian *et al.* demonstrate how different concerns in the WEF nexus intertwine. This paper explores the interwoven concerns within the energy, water, and food policy areas, emphasizing the importance of understanding their interrelationships and addressing them holistically. The study considers the nexus primarily from a developing country perspective and highlights the need for systems thinking and a modelling framework to propose effective national policies and regulations. With this in mind, Bazilian *et al.*[22] identified different perspectives through which the energy-water-food nexus can be viewed. Depending on the chosen perspective, either water, food, or energy is considered the primary resource, while the others are seen as inputs or users. This perspective significantly influences policy design and priorities but often lacks a global vision of the entire WEF nexus problem. For this reason, in order to avoid bias and ensure the design of more sustainable public policies, Bazilian *et al.*[22] point out important parameters that must be considered. These parameters include challenges related to resource access and quality, rapid global demand growth, resource constraints, the global nature of these goods with international trade implications, regional variations in availability and demand, interdependencies with climate change and environmental issues, security concern Fig. 2 illustrates the interactions within the WEF nexus identified by Brazilian from a security focus. Based on this figure it becomes evident that the spheres of energy, water, and food significantly impact each other, and disregarding the effects in one sphere can have substantial repercussions on the others. Anticipated bottlenecks and constraints in these resources pose political, economic, and management challenges, emphasizing the necessity for a systematic and coordinated planning approach.

Additionally, Bazilian *et al.*[22] emphasized the urgency for a unified framework that comprehends and addresses the interactions between energy, water, and food policies. Key points discussed include the necessity for integrated tools to support decision-making, policy assessments, policy harmonization, technology assessments, and scenario development. They highlighted the lack of robust analytical tools, conceptual models, algorithms, and data sets to provide insights into the

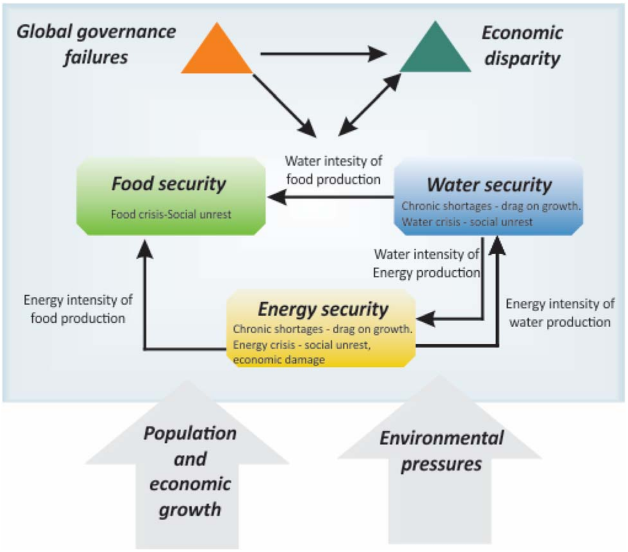

Fig. 2 Nexus scheme relationship with security focus studied by Bazilian *et al.*[22]

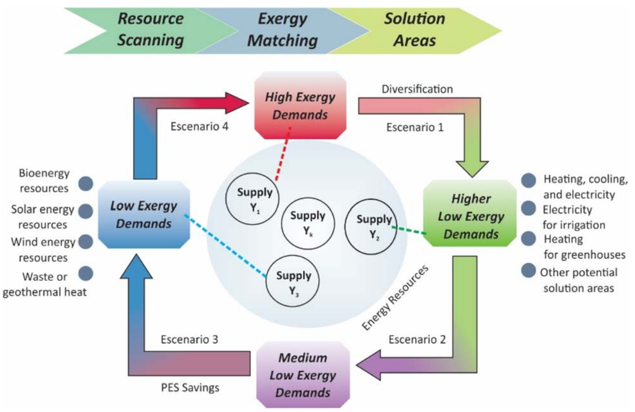

Fig. 3 Scheme of the method of improving circular economy on the dairy farm proposed by Kılkış & B. Kılkış.[47]

future use of these resources. Various established practices such as life cycle analysis, exergy analysis, complexity theory, operations research, material flows analysis, industrial ecology, and sustainable supply chains are referenced.

Based on the aforementioned, Bazilian *et al.* [22] acknowledge previous attempts to analyze aspects of the WEF nexus, including The Limits to Growth and the WELMM approach. They also acknowledge progress made in integrated assessment models for energy and land use but point out the limited integration of water use. In response to these shortcomings, Bazilian *et al.*[22] introduced a new modeling framework called Climate, Land, Energy, and Water (CLEW). The CLEW framework aims to offer a more integrated, multi-resource representation with improved geographical coverage and accessibility, especially for developing countries. The CLEW framework intends to empower decision-makers and policymakers to assess the impacts and trade-offs of different options within the broader CLEW system. Its objective is to facilitate the development of cost-effective policies that achieve multiple objectives, harmonize conflicting policies, assess technology options, and establish consistent scenarios for future development trajectories. However, it is not yet a fully integrated tool.

Based on the experiences acquired from the previous paper, Bazilian *et al.*[34] studied the complex relationship between energy, water, and food policies. They determined how these factors are interconnected and require systems thinking approach to understand various concerns, including environmental impact, national security, and price volatility. Due to the complexity and vastness of each individual area, there was limited research on how to support decision-making at the intersection of these spheres. Algal bioresources were used in this article as a case study due to their potential to transform energy resources, food supplies, and greenhouse gas mitigation. This work examined the energy-water-food nexus through the lens of algal bioresources, introducing several considerations such as weighing the costs and benefits of producing fuel or food, sensitivities to water quality, climate change emissions, the use of waste streams like flue gas or wastewater, and energy and food security issues. Bazilian *et al.* determined that the assessment and optimization of these systems can be complicated by various stakeholder interests and the need to incorporate factors from economics to social impacts. Techno-economic analysis (TEA) and life-cycle assessment (LCA) were used to assess microalgae for fuel production in order to address the U.S. national algal biofuels technology roadmap. Their findings highlighted reasons for the increased interest in algal biofuels, including high per-acre productivity, non-food-based feedstock resources, use of non-productive land, versatility in water sources, production of biofuels and valuable co-products, and potential for recycling CO_2 and other nutrient waste streams. Finally, they concluded that algal systems present a unique opportunity to study the energy-water-food nexus. Understanding the potential benefits and impacts of these systems requires an amalgamation of science, technical, life-cycle, financial, and policy analysis. A consistent framework that accounts for the design and operational flexibility of algal systems will enable robust decision-making and help identify risks and mitigation strategies. This information can inform policy and investment decisions, research and development prioritization, and dialogue related to the energy-water-food nexs and sustainability.

On the other hand, in 2012, Prasad *et al.*[35] presented a planning and modeling project which acknowledged that the WEF nexus tools offer improved resource use and policy coherence in South Africa. Prasad *et al.*[34] also helped in the analysis and conception of how the WEF nexus creates opportunities to increase resource efficiency by ensuring sustainable access to water, energy, and food thus improving policy coherence.

By 2014, De Laurentiis *et al.*[36] presented a study between the connections and interactions of the WEF nexus. In this study, they demonstrated how the independency of one of the nexus resources will not create any good results. In other words, food security cannot be achieved without energy or water security. An important aspect of their work is the assurance that sustainability can be promoted by safeguarding the WEF nexus.

Walker *et al.*,[37] also in 2014, explored the issues of sustainability and the effect of human behavior on city metabolism. They approached the WEF nexus as a research tool to aid with investment and policy decisions. With a multi-sectoral analysis, they were able to generate resource estimates, reveal the synergy and interaction between WEF. They were also able to estimate the benefits in terms of economics and environmental impact. Their results suggested that better and newer technologies for urine separation, food and waste collection in conjunction with algae cultivation can bring sustainability to the city of London.

It is important to note that in 2015, the number of publications addressing the concept of sustainability in the WEF nexus increased with the aim of support and achieve the recent propose Sustainable Development Goals (SDGs) by United Nation. As proof of this, Ozturk[38] examined the food-energy-water nexus in the BRICS countries (Brazil, the Russian Federation, India, China, and South Africa) and explored the dynamic links between energy, food, water, public health, economic growth, and the environment. He used three models and panel data spanning from 1980 to 2013 to analyze the relationships and identify policy implications. The goal of this work was to investigate how health, wealth, and the environment are interconnected and extract lessons for policy development. In addition, a food security index was developed using principal component analysis, which brings together factors like agricultural machinery, cereal production land, and agricultural value added. These variables were assigned individual weights, and the food security index was used as the main variable in the food model. The study also scrutinizes the potential relevance of the Environmental Kuznets Curve (EKC) hypothesis among BRICS nations. The results reveal that energy shortages and inadequate water resources negatively impact food security in the BRICS countries. Economic growth contributes to increased energy demand and environmental degradation. The depletion of forests and natural resources hinders economic prosperity, driven by rapid industrialization, domestic investment, improved water sources, and labor force participation. The study also finds evidence supporting the Environmental Kuznets Curve (EKC) hypothesis, showing an inverted U-shaped relationship between carbon dioxide emissions and economic growth in Brazil, India, and South Africa. Given these findings, the study suggests the following policy recommendations:

- Short-term: manage climate variability by effectively using renewable energy, improving land use, and ensuring adequate water resources to increase agricultural productivity and counter the effects of crop failures and biodiversity loss.
- Medium-term: develop resource-based policies that secure agricultural water availability, vital for fighting global food insecurity. These policies should aim to enhance land fertility and productivity.
- Long-term: promote the integrated modeling of the food-energy-water relationship to address global sustainability challenges. This requires comprehensive strategies and policies to understand and address these interdependencies, ensuring long-term sustainability.

Based on these suggestions, Ozturk[38] underlines the need for a diverse energy mix to improve health infrastructure, stimulate economic growth, and lower carbon emissions in BRICS countries. Domestic investment and an active labor force are critical for enhancing food security and water resources. The study also stresses the importance of conserving biodiversity as increasing energy demands lead to natural resource depletion. The EKC can offer solutions for sustainability and food security in the BRICS nations.

On the other hand, Heckl *et al.*[39] propose the use of P-graph, a tool framework, as an effective means to design alternative networks that represent the WEF nexus for the purpose of achieving more cost-effective and sustainable options. P-graphs are bipartite directed graphs that guarantee an unambiguous representation of any process. They are based on combinatorial analysis and rigorous axioms which prove useful in the initial phase of WEF nexus design.

Al-Ansari *et al.*[40] suggest an integrated tool for the life cycle assessment of WEF. This WEF nexus modeling tool can provide an environmental assessment of food production systems with a holistic and sustainability approach. Al-Ansari *et al.* were able to prove that the food sphere within the WEF nexus is the largest contributor to global warming. And that, with the use of renewable energy, greenhouse emissions can be reduced by almost a third, which represents a growth in terms of sustainability for any study region.

Leck *et al.*[18] review different approaches to the WEF nexus. They examine the problems of interdisciplinary collaboration, complexity, political economy, and the incompatibility of the institutional structures present. The importance of their research is that the challenge to recognize the disciplinary boundary crossing the WEF nexus and the sustainability agenda promotes was achieved. Thus, it becomes crucial to establish sustainability and the WEF nexus approach as part of a broader repertoire of responses to the global environmental crisis.

In 2016, El Gafy *et al.*[41] used system dynamics models to create a new approach to analyze dynamic behavior by focusing on the WEF nexus interactions. Their model first establishes an energy and water footprints in crop production and consumption. Secondly, a virtual water and energy export and import. Thirdly, an energy and water saving balance in agricultural production. And lastly, a WEF nexus index. The case study, created in Egypt, established that an intersection of human welfare, poverty reduction, and sustainable development issues is generated by the WEF nexus.

Irabien & Darton[42] studied the WEF nexus in the Almeria region (Spain) regarding the tomato production. They followed a process analysis method connected to market demands and ecosystem services. Their results estimate that the evolution of ecosystem services, the main constraint of the system, will generate sustainability in the region while carbon, water, and chemical footprints are useful for sustainability assessment.

Yang *et al.*[43] show that it is critical to jointly address the challenges of WEF security. They evaluated Pakistan's Indus River WEF nexus using the Indus Basin Model Revised-Multi Year. They modeled the impact of WEF with a range of climate change scenarios, and under various alternative water allocation and water infrastructure development mechanisms. They found that the appropriate use of the WEF nexus interactions can mitigate the negative effects of climate change on agricultural water, energy use and generate a framework for sustainability.

Keairns *et al.*[44] propose that the WEF nexus analyses, computational modeling and life cycle assessment, require new frameworks and tools to integrate technical and social dimensions. Their results demonstrate the importance of a systemic view integrated to the complex interrelationships of the WEF nexus in planning solutions that achieve sustainability goals.

Smajgl *et al.*[45] convey a new perspective on the balance of sectoral aspects that are potentially problematic in the large-scale development of water, energy, and food resources. They hypothesize a dynamic WEF nexus framework linked to state changes. In addition, they demonstrate the ability to reveal the cross-sectoral connections of the WEF nexus, in a sustainability framework as well.

While the conceptual framework for a sustainable design of the WEF nexus has been transcendental over the past few years, in 2017 a series of works that strongly contributed to the inherent connection between the WEF spheres and sustainability was presented. Research work such as that reported by Weitz *et al.*[46] promoted the WEF nexus as a popular concept in environmental impact research and policy debates. It was also suggested by Weitz *et al.*, that there are advocates of the WEF nexus approach to reaching governance agreements. However, the identification of obstacles in the coherence of the WEF nexus approach was amongst the most relevant. They drew insights from research streams and discussed the distinction between different communicative, organizational, and procedural instruments; from which the communicative instruments aim to influence visions and long-term goals through sustainable development strategies and national environmental plans.

Kılkış & B. Kılkış[47] conducted a pioneering study on the incorporation of circular economy principles within the framework of the water–energy–food (WEF) nexus. The paper highlighted the potential advantages of merging these two concepts to achieve Sustainable Development Goals (SDGs) on a global level. They suggested that this integration could meaningfully contribute to three specific United Nations' SDGs, namely food security (SDG 2), sustainable water management (SDG 6), and affordable, clean energy (SDG 7).

Kılkış & B. Kılkış[47] emphasized how circular economy policies help to evaluate and preserve a country's resources while advocating for environmental restoration and improvement. Concurrently, adopting the WEF nexus framework strengthens global resource security by bridging disparate studies. They concluded that the circular economy and the WEF nexus are inherently interlinked. In contrast to the unsustainable methods of a linear economy, a circular economy strategy aims for restoration and regeneration. This offers a practical solution to escalating resource scarcity, which leads to geopolitical strife, supply risks, and unstable circumstances. The mutual interdependence of these areas of research is evident, and a combination of WEF nexus and circular economy policies could be crucial in ensuring sustainability.

They also examined the European Union (EU)'s nexus policy, which has struggled to efficiently cooperate with the environmental sector to address governance problems. However, the EU has successfully transformed its economic structure by implementing the circular economy policy. This has led to job growth and waste reduction due to more careful resource use. Still, the EU's current biofuel support policies operate in a vacuum, overlooking their impact on other sectors and their long-term viability. Policy-making that incorporates both the circular economy and WEF nexus frameworks can guarantee resource security and sustainable development by reducing waste.

The study proposed an approach, represented in Fig. 3, to guide organizations and future researchers in assessing sustainability and implementing environmental security. The method involves analyzing the flow of end-use materials for sustainable resource procurement within the integrated WEF nexus and circular economy framework. Moreover, the water, energy, and food sectors should be consolidated under one umbrella to initiate symbiotic benefits that enhance the cross-sector integration of resources.

The paper consistently emphasized the nexus as a key tool leading to a circular economy, the ultimate sustainability goal. Recycling waste and other byproducts throughout the supply chain promotes resource circularity and prolongs product life. In this context, Life Cycle Assessment (LCA) can be used to evaluate the environmental impact and set standards for remanufacturing assessments.

Additionally, Zaman *et al.*[48] clearly demonstrate that the environmental sustainability agenda is committed to water, energy, and food resources. They employ a study in which they model different perturbations in WEF resource variables in contrast to the generation of atmospheric pollutants in various African countries. The results of Zaman *et al.*[48] reaffirm that there is a strong relationship between WEF resources and atmospheric emissions, and that, if a sustainable future is desired, optimal models of the WEF nexus must be designed for each specific region.

In 2017, Heard *et al.*[49] showed that urban systems require water, energy, and food which are often out of reach, and the consumption of these resources generates major environmental problems. Heard *et al.*[49] state that the three WEF spheres are facing increasing demands and limitations of utmost importance in the conservation of a sustainable world. In their study, it was evidenced that the greater the urbanization area, the greater a large-scale sustainable solution must to be applied. And that by studying the interactions and connections of the WEF will facilitate the complex challenge of sustainability.

Al-Ansari *et al.*[50] illustrate how the sustainability of the food production system is closely related to the WEF nexus. They used the WEF nexus tool to model the interdependence between resources while performing an environmental assessment for the State of Qatar. Kurian,[51] argues that effective implementation of the WEF nexus can be supported by robust science. The WEF nexus approach must introduce concepts from transdisciplinary approaches to sustainable development.

Ozturk[52] provides an overview of the relationship of WEF resources and sustainability in agriculture. He mentions that the livelihood of those affected by food security, access to water resources or electricity can be benefited by generating the WEF-sustainability nexus relationship. His work, which focuses on Africa's poor countries, examines the dynamic nexus between agricultural sustainability and food poverty. The results reveal that the agricultural value added to the nexus significantly decreases WEF poverty, leading to higher economic growth and price levels at the cost of environmental degradation.

Overall, agricultural sustainability is a prerequisite in the reduction of WEF poverty. Al-Saidi, & Elagib[53] conducted an intensive literature search to reveal, first of all, the rationale behind the WEF nexus debate, and secondly, to identify the diverse tools in the analysis of the WEF nexus interrelationship in a science and policy framework. Three factors that promote the WEF nexus concept were identified. The first factor considers the uncertainty of interrelationships; the second factor deals with the resource supply crisis; and the third factor manages strategies. Their work creates a debate on nexus governance and opens the link to a sustainability discussion.

As far as studies related to the water–food–energy nexus are concerned, there has been an increase in the number of papers addressing the problems of water scarcity and drought since 2018. This is partly due to the increasingly evident effects of climate change. Among the most notable works in this area is the research carried out by Zhang *et al.*[54] They performed a research with the objective of developing an effective agricultural drought management system by integrating real-time drought monitoring with real-time irrigation management using an integrated water–food–energy nexus modelling and optimization approach. This study is specially focused on investigating the impact of drought and irrigation management on corn production in Nebraska. Using a spatially explicit water–food–energy simulation and optimization method, applied to one of the most important corn regions in Nebraska. The optimization problem considers different criteria to determine the best solution, including crop yield, energy consumption, water use, and economic feasibility., The crop simulations were validated with yield statistics. The optimization algorithm generated a Pareto frontier, which is a set of optimal solutions that satisfy different trade-offs between these criteria.

Additionally, this research allowed to integrate a crop model and OptiCE (GIS-OptiCE), an optimization tool for clean energy systems, to evaluate the effects of drought on corn production. This combination provided guidance on optimal irrigation requirements using the water–food–energy nexus approach. The study's novelty lies in its foundation for a comprehensive management tool for irrigation, enabling near real-time drought management and optimal irrigation guidelines. Therefore, their results provided a tool to determine the best balance between these criteria for effective agricultural drought management.

It found that drought conditions, like those experienced in 2012, can reduce corn yield by up to 50% compared to wetter years like 2009. The simulation results demonstrated the crucial role of irrigation in preventing crop losses due to drought and sustaining high yields. However, the study also highlighted the need for significant investments in water and energy to mitigate the negative effects of drought. The water–food–energy relationship indicated that irrigation plays a vital role but requires substantial resources. The multi-criteria optimization problem, showed that the optimal crop yield does not necessarily correspond to the maximum potential crop yield, as lower crop yields can also result in potential water and energy savings depending on environmental and economic constraints. On the other hand, based on the results of the optimization problem, Zhang *et al.*[54] also demonstrated that irrigation plays a key role in limiting crop losses due to drought and sustaining high yields of up to 20 t ha^{-1}. However, the study also showed that significant investments in water and energy are required to limit the negative effects of drought. Finally, they stablished that Future studies will aim to integrate a hydrological model to analyze water balance at different spatial and temporal scales. The study's multi-criteria optimization problem revealed that the optimal crop yield does not always align with the maximum potential yield. The optimization algorithm's Pareto frontier demonstrated that optimal solutions could lead to lower crop yields, resulting in potential water and energy savings depending on environmental and economic constraints.

Following the line of drought studies, Campana *et al.*[55] proposed to manage agricultural drought in Sweden using a spatially explicit model which considers using a water–food–energy nexus perspective. Their study applied a comprehensive approach that combines knowledge and data of different fields such as climatology, agriculture, and energy systems. In this sense, the model integrated spatial climatic data to evaluate the effects of drought on potato crops in Sweden. The mathematical model was applied to assess the impact of drought on the Swedish irrigation sector in 2013 which is considered a particularly dry year. The simulations shown that if no irrigation is applied during a drought year, significant crop yield losses can occur, up to 50% of the potential yield. Therefore, to avoid crop failure, significant amounts of water and energy need to be invested to maintain high crop yields. In the study area, the worst situation in terms of water and related energy requirements for irrigation was about 350 mm and 700 kW h ha for 2013. In general, the study of Campana *et al.*[55] provides important insights into managing agricultural drought in Sweden, highlighting the need for integrated water–food–energy nexus models to assess the impact of drought on crop yield, water availability, and energy requirements for irrigation. The research aims to provide real-time guidelines for managing drought and has significant potential for precision agriculture applications.

T.-S Uen *et al.*[56] established that reservoirs play a critical role in the WFE nexus since they provide water for agriculture, energy production, and domestic use. However, the complex linkages and multifunctions associated with the WFE nexus represent an important challenge to synergistically optimize the benefits associated to the reservoirs. It is for this reason that T.-S Uen *et al.*[56] proposed a holistic three-fold scheme that integrates the short- and long-term joint operation of a multi-objective reservoir with irrigation ponds to optimize the benefits of the WFE Nexus. The study was applied to the Shihmen Reservoir and 745 irrigation ponds located in Taoyuan City, Taiwan. The three-fold scheme implies optimizing short-term (daily scale) reservoir operation to maximize hydropower output and final reservoir storage during typhoon seasons. On the other hand, the authors also simulated long-term (ten-day scale) water shortage rates, taking into account the availability of irrigation ponds for both agricultural and public sectors during non-typhoon. With this in mind, the authors proposed the synergistic benefits of the WFE Nexus in a year-round perspective by integrating the short-term optimization and long-term simulation of reservoir operations. Their results showed that the proposed methodology can increase hydropower output, reduce agricultural and public water shortage rates, and increase food production from a year-round perspective. Specifically, the optimal short-term reservoir operation obtained from the non-dominated sorting genetic algorithm II (NSGA-II) can largely increase hydropower output but only slightly affect water supply. The simulation results of the reservoir coupled with irrigation ponds indicated that joint operation can significantly reduce agricultural and public water shortage rates by an average of 22.2% and 23.7%, respectively, compared to those of reservoir operation excluding irrigation ponds. The integration of short- and long-term joint reservoir operation and irrigation ponds can not only improve energy production but also enhance water supply and food production.

Furthermore, Trabucco *et al.*[57] explored the concept of the water–energy–food nexus in a case of study focused on Sardinia, an Italian region which was facing several challenges such as water scarcity, food security, energy management, and climate change impacts. The study identified interactions with other Nexus sectors, including feedback processes, and used stakeholder involvement to inform the development of policies, goals, and tools for the Sardinian case study. According to Trabucco *et al.*[57], Sardinia has a population of 1.6 million and economy primarily based on tourism (17% of GDP) and agriculture (4% of GDP). The available water resources can only satisfy 53% of the regional demand, with agriculture consuming most of the water (69.4%) and urban (25.4%) and industry (5.2%) using the rest. Water availability and demand vary across the region's seven hydrological districts, posing potential water security threats, especially with the growth of the agricultural, tourism, and energy sectors under climate change scenarios. The nexus model was developed to account for water supply and demand related to agricultural, energy-related, and domestic/tourist consumption. The model also took into consideration energy generation and consumption, along with other aspects regarding climate, tourism, food, and land use. The model also accounts for the inflows to reservoirs based on precipitation partitioning to runoff, with water supply for the main reservoirs and water demands aggregated at the island level. The model also considered different factors such as open-water evaporation from reservoir surfaces, discharges for hydroelectric generation, spillways in times of overflow, irrigation requirements, industrial water demand, domestic and tourist water requirements, and environmental flows. The crop water requirements and area planted for 13 major crops on Sardinia were modelled under current and changing climatic conditions. Energy production and demand, as well as touristic fluxes and relative water demands, were also modeled.

The model for Sardinia runs simulations from 2010 up to 2050 under different climate scenarios with a total of 73 variables accounting for each nexus sector and the interlinkages between them. According to Trabucco *et al.*[57], this model provides a reasonably accurate representation of the nexus in Sardinia, offering useful insights for policy decision-making in light of climate change. The results obtained by Trabucco *et al.*[57] indicated that the energy generation is predicted to decrease by about 20% in 2030, primarily due to a reduction in fossil-based energy generation that is not entirely offset by greener energy sources. Despite the decrease, the generation is expected to match consumption every month. However, increasing pressure from the tourist sector, particularly during summer, could strain the system. The transition to greener energy may take longer than anticipated if this strain intensifies. In addition, the simulations also showcased the irrigation water demand under both current and future climatic conditions. While the summer peak demand is expected to remain similar, due to an increase in spring water requirements. The future could see an increase in irrigation requirements during the spring but a decrease in the fall, primarily due to changes in seasonal precipitation patterns. These changes are anticipated to become more pronounced by 2050, thereby intensifying the pressure on both the water and energy systems.

In this sense, the investigation highlighted the importance of choosing appropriate levels of model spatial disaggregation to produce reliable model outputs. This choice is heavily influenced by spatial variability of different physical and socio-economic conditions, which is often brought to light by local expert stakeholders. The decision has substantial implications for any further analysis and potential policy recommendations.

Using the whole reservoir system in Sardinia as a unique geographically lumped aggregated system led to overestimations in the efficiency to store and redistribute water across the island. To more accurately represent resilience in water supply to climate changes and capacity to meet demand, the final model development will be disaggregated into seven hydrological basins. This will better reflect spatial variability and capture hydrological dynamics across the island. Aggregation for the entire island will then take place, providing a more accurate spatial representation that leads to improved knowledge for policy and decision making.

It was also discovered that a collaborative and constructive stakeholder involvement, coupled with detailed policy analysis, is crucial for the development of meaningful Nexus models. This should be implemented from early stages. However, encouraging stakeholders to expand their experience beyond their specific sectors (breaking 'silo thinking') presented several challenges. Overcoming these required cooperative forums that brought together a diverse range of stakeholders to determine the important case-study nexus sectors, critical interactions between these sectors, data availability, and the main policy-relevant formulations that the model should try to include. The policy analysis for the case study was recognized as central to these efforts.

Shumilova *et al.*[58] discussed the problem of water scarcity, which is becoming a global issue due to uneven distribution caused by climate change, land use alteration, and increasing human exploitation. In this sense, their work studied Water Transfer Megaprojects (WTMPs) as possible solutions to address this problem. These projects involve large-scale engineering interventions to transfer water within and between river basins, with the goal of providing water for human welfare and supporting agriculture, energy production, mining, ecosystem restoration, and navigation. This study collected data on 34 existing and 76 planned, proposed, or under-construction WTMPs and found that the total volume of water transferred by future projects could reach 1910 km^3 per year, with a total transfer distance of more than twice the length of the Earth's equator. The largest future WTMPs are located in North America, Asia, and Africa, and the predicted total investment will exceed 2.7 trillion US$. The study notes that the scale of these projects means their impacts will cover regional and continental scales and may be irreversible. They found that although WTMPs could help meet increasing water demands, the study raises concerns about their social, environmental, and economic costs. The lack of reliable data on the impacts of future WTMPs is also a limitation. Therefore, the authors have emphasized the need to develop internationally agreed criteria for their assessment. In this sense, green infrastructure, such as using recycled water, improving existing systems, and increasing irrigation efficiency, should be considered as alternatives or part of a combined solution to address water scarcity challenges.

On the other hand, during this time, there have also been works that study the nexus in the context of biofuel production. One example is the work presented by Moioli *et al.*[59] In this paper it is explored the sustainability of 1st generation biofuel production from a point of view of the water–food–energy nexus. The nexus approach proposed by Moioli *et al.*[59] consider the interrelated nature of water, food, and energy production and how changes in one area can affect the others. Based on the nexus approach, it is proposed a new index called the nexus index that evaluates the efficiency of biofuel production processes in relation to the use of natural resources such as water and land. The index highlights the most sustainable production processes and places, and it suggests possible improvements to move towards greater sustainability. The objective of this index was to provide a comprehensive assessment of the sustainability of producing biofuels considering the complex interrelationships between the different components of the WEF nexus. By analyzing the efficiency of biofuel production processes. Additionally, this study identified countries with the capability of producing sustainable fuels from some crops. The results obtained demonstrates that the efficiency of production can vary greatly from one country to another due to differences in agricultural practices, resources availability, harvest polices and demand. Finally, their research aims to assist decision-makers in designing energy policies that make the best use of a country's resources and balance the competing demands of water, food, and energy production.

Li *et al.*[60] developed an optimization model for the sustainable management of the WEF nexus in irrigated agriculture, which is a primary user of the world's freshwater resources and a major producer of food. The study aimed to allocate resources to obtain maximum economic benefit while minimizing environmental impact, given the large uncertainties involved. To achieve this, the study applied a multi-objective programming framework with random-boundary intervals and stochastic chance-constrained programming to solve the model. The developed model aimed to provide policy makers with cost-effective and environmentally-friendly strategies and policies. This model was applied in an irrigation district in northeast China to demonstrate the applicability of the model. The study identified the interactions among water, energy, and food subsystems in the irrigated agricultural system for mathematical modeling, which helped optimally allocate limited water, land, and energy resources. This mathematical model integrates fuzzy set theory into the optimization modeling framework which allow it handling complex uncertainties and generating realistic solutions. Their results shown that the model is efficient in computational terms, in addition, this model is capable of generating cost-effective and environmentally-friendly strategies and policies.

In 2019 with the rise of artificial intelligence, some interesting work emerged such as the study proposed by Zhou *et al.*[61] In this study it is explored the integration of small-hydropower generation into existing water supply systems, leveraging artificial intelligence techniques to harness the water–food–energy (WFE) Nexus's synergies. The focus was on the Shihmen Reservoir and its water supply system in northern Taiwan, serving public and agricultural sectors. This research provides new perspectives on cleaner energy production through WFE Nexus synergies. It also proposes executable strategies for policymakers on small-hydropower practices for sustainable development, contributing to future energy needs. The study's innovation lies in the integration of existing water supply systems and small-hydropower installations using AI and multi-objective optimization techniques to stimulate the WFE Nexus's synergistic benefits.

The study focuses on the Shihmen Reservoir located in northern Taiwan, a crucial multi-purpose reservoir that supports the Taipei metropolitan area. The reservoir has an effective storage capacity of 201 million m^3 and a watershed area of 763 km^2. The main river in this watershed is the Tamsui River. The Shihmen Reservoir maintains a regular water supply to the demanding sectors. For instance, water released from the reservoir through the Shihmen Canal serves the public (domestic and industrial) and irrigation sectors in South Taoyuan. The reservoir also regulates water to the Shihmen Hydropower Station, the Houchih Weir, and other sequential weirs. Any excess water is directly released from reservoir spillways to the Houchih Weir if the public and irrigation water demands in areas other than South Taoyuan exceed the maximum discharge capacity of the Shihmen Hydropower Station.

The Shihmen Reservoir authority implements M-5 rule curves for making trade-offs in water supply between public and irrigation sectors. This includes adapting the water allocation system to fully meet water demands if reservoir storage capacity exceeds the lower limit curve, and adjusting the ratio of water released to irrigation and public sectors based on reservoir storage levels. The study revolves around the water supply from the Shihmen Reservoir to the public and agricultural sectors, with the objective of assessing the scheme of small-hydropower installation and its output under different operational durations. The data used consists of a total of 504 reservoir inflow datasets collected over 14 hydrological years, from July 2002 to June 2016, and the average water demands of the years 2015 and 2016.

The methodological approach used involves two components: multi-sectoral water allocation optimization and small-hydropower installation (output) optimization. Given the constraints of reservoir storage capacity and uncertain hydrological conditions, it is challenging to balance water allocation reliability and the synergies of the water–food–energy (WFE) Nexus. To tackle this, the researchers employed an Artificial Intelligence (AI)-based optimization framework. The water allocation to the public and agricultural sectors was first optimized using the Non-dominated Sorting Genetic Algorithm (NSGA-II), based on the 14 year reservoir inflows. Subsequently, the small-hydropower installation (output) was optimized using the Genetic Algorithm (GA), with the optimal water allocation results serving as inputs. Ultimately, the synergistic benefits of the WFE Nexus under different hydrological scenarios were driven by the combination of optimal outcomes of multi-sectoral water allocation and the output of small-hydropower turbines. The study used the historical reservoir operation based on the M-5 rule curves as a benchmark for comparison.

The research demonstrated that the optimized multi-sectoral water allocation (obtained from the NSGA-II) combined with the optimal small-hydropower installation (obtained from the GA) can mitigate water shortage, enhance water storage to reservoir capacity ratio, and boost hydropower output without reducing water supply. This approach has implications for increasing energy output, improving water supply efficiency, and enhancing food production, both for year-round and multi-year reservoir operations. The study highlights that the proposed methodology provides a strategy for small-hydropower management that can support green growth and effective WFE nexus management amidst growing urbanization. Moreover, it acknowledges the need for green energy solutions, such as Small Hydropower Plants (SHPs), given the upcoming phase-out of nuclear power in Taiwan by 2025. It also notes the potential for future integration of other renewable energy sources, such as solar PV power and wind power, with optimal water allocation.

However, despite its potential, small-hydropower has been relatively neglected in Taiwan, primarily due to high hydrological uncertainty and low purchase prices compared to other green energy sources. The study proposes that its model could be used to explore the potential of SHPs as a guideline for sustainable energy development, with the hope that advances in SHP techniques and economies of scale will improve the profitability and adoption of these systems in the future.

Liu *et al.*[62] proposes a study to investigate the interplay between water, food, and energy (WFE) in China and propose a solution that supports sustainable food production and conserves hydropower potential. The authors used artificial intelligence techniques and a three-faceted approach, including optimizing multi-sectoral water allocation, maximizing small-hydropower installation, and leveraging the synergistic benefits of the WFE Nexus. This study was applied the Shihmen Reservoir in Taiwan and found that the proposed optimal water allocation and small-hydropower installation scheme could effectively alleviate water shortage conditions, boost food production, and increase hydropower output. In addition., this study explored new perspectives on cleaner energy production and provide policymakers with strategies for sustainable small-hydropower practices.

Zhang *et al.*[63] presented a paper which has the objective of providing comprehensive literature review of the water–energy–food (WEF) nexus, with a focus on the urban WEF nexus, and to develop a conceptual framework for scientific analysis and policy-making related to the urban FEW nexus. The investigation resulted in a proposed three-dimensional conceptual framework of the urban WEF nexus, which provided a perspective on resource interdependency, resource provision, and system integration. This framework was useful for the systematic modeling and integrative management of the complex nexus issues of urban systems. The paper identified future directions for urban nexus research, such as systematic characterization, cross-region tele-connection mechanisms, co-decision model development, and governance transition. The authors emphasized the need for quantitative and integrated models at different levels to realize collaborative management and advance WEF governance practices through real-world applications.

Ghafoori Kharanagh, *et al.*[64] proposed a study that focuses on analyzing the social network of actors in the water–food–energy (WFE) nexus in the Yazd-Ardakan aquifer, Yazd province, Iran, using social network analysis (SNA) criteria and multi-criteria decision-making (MCDM) model ELECTRE I to identify the powerful actors and power structure in the nexus network. The aim is to improve groundwater governance by involving powerful actors in decision-making and policymaking for sustainable development. The study identifies that the power structure in the WFE nexus network is not at equilibrium, and most of the power lies with the public sector. The findings suggest empowering weaker actors by improving their relationships with powerful actors and involving them in the decision-making process. The motivation behind this investigation is to address the major water governance concern of coordinating the complex relationships of the water, food, and energy sectors for sustainable development and prevent the transfer of problems from one sector to another. The study highlights the nexus approach as a novel method to represent the interrelated challenges of the water, food, and energy sectors by considering the sectors' policies to achieve sustainable development.

Kamrani, *et al.*[65] developed a performance appraisal framework for agricultural water distribution systems based on the water–food–energy nexus perspective. The study analyzed and evaluated the operational management of various agricultural water distribution systems, including traditional and automatic control systems, under conventional and water shortage scenarios in a study area located in central Iran. The WEF indicators were calculated for performance appraisal, and the results showed that upgrading the manual operation to an automatic control system provided the best results from the nexus indicators perspective. The study also used Bayesian Network models to present a probabilistic approach that could assist managers and decision-makers in evaluating the performance of the system, based on the nexus perspective. The developed framework can be employed as a decision support model to prioritize options for modernizing agricultural water distribution systems. The framework developed in this study can be employed to upgrade the main water distribution system and the lateral distribution system in the future. Finally, the authors suggested developing a comprehensive framework for evaluating agricultural water management that includes water distribution and application by developing the mathematical model of water application systems on the farm scale and linking it to the distribution system.

Do *et al.*[66] studied the effects of reservoir operation on hydropower generation, irrigated crop production, and fisheries yield in the Tonle Sap Lake through a novel hydro-economic model at the whole basin scale. The study was motivated by concerns from stakeholders that highlighted three major trade-offs between hydropower and irrigation, hydropower and fisheries, and irrigation and fisheries. The results indicates that trade-offs between sectors can be turned into synergetic opportunities. For instance, reservoir operation can increase water availability for irrigation without severely harming hydropower production, raising irrigated crop revenue by 49% and reducing crop losses during droughts by 30%. Additionally, eco-friendly management can increase fisheries yield by up to 75%, but it decreases both irrigated crop production (−48%) and power production (−17%). The authors concluded that decision-makers need to adapt to irrigation demand and hydropower production to prioritize water availability for hydroelectricity, irrigated crops, and fisheries. Developing integrated irrigation and aquaculture systems could be one of the solutions for downstream farmers and fishers.

Zhou, *et al.*[67] proposed a system-wide solution that utilized hybrid hydro-floating photovoltaic power generation to promote water–food–energy (WFE) nexus synergies. A multi-objective optimization model was developed to maximize hydro-floating photovoltaic power output, the ratio of water storage to reservoir capacity, and the ratio of water supply to water demand. The study was carried out in the Shihmen Reservoir watershed and its WFE system in northern Taiwan. The findings showed that the proposed optimization model could significantly enhance the synergistic benefits of the WFE nexus, with water storage, food production, and hydro-floating photovoltaic power output improving by 13%, 13.3%, and 15.1%, respectively. The optimal tilt angles of floating photovoltaic installation were found to vary between −11.9° (Summer) and 44.3° (Winter). The study was motivated by the goal of creating new opportunities for green energy production and supporting policymaking with feasible plans for floating photovoltaic deployment that prioritize social sustainability. In conclusion, the study highlighted the potential for complementary operation between floating photovoltaic and hydropower generation to improve water–food–energy nexus synergies and promote practical solutions for renewable energy exploitation in the interest of a more sustainable environment.

Sun *et al.*[68] developed a water–food–energy (WFE) nexus model which used the chance-constrained fuzzy fractional programming (CFFP). The mathematical model incorporates water resources utilization, agricultural land allocation, and electricity generation into the nexus framework in Kaikong watershed, a water-scarce region in northwest China. The authors determined that uncertainties in water availability, demand, and pollutant/CO_2 emission had significant effects on agricultural and electric productions. The CFFP-based WFE model effectively handled multi-objectives expressed as output/input ratio problems in a fuzzy and random environment. The unit water benefit varied from 0.852 to 0.926 $ per m^{-3} across 144 scenarios. The study recommends controlling irrigated agricultural areas below 203.4 × 103 ha and encouraging vegetable cultivation. The proportion of fossil-energy power was optimized within 53.1–60.4% in adaption to water and environment constraints. Finally, the study provides optimal strategies for sustainable resource usage, promoting water-use efficiency, and mitigating environmental emissions. The results can be useful for other water-stressed regions like Kaikong watershed. The CFFP method has been shown to enhance the management of WFE nexus systems under multiple uncertainties, represented as fuzzy sets with membership functions and random parameters with probabilistic distributions.

Although renewable energy technologies have been described as the antidote for achieving environmental sustainability, however, a sustainability assessment revealed that while fossil fuel energy technologies compete with water withdrawal and consumption, some renewables compete with food for land-use—a situation that requires cost and benefits policy estimation. The work by Sarkodie & Owusu[69] highlights that the effect of water–energy–food nexus on environmental sustainability depends on several socioeconomic factors that require attention. Thus, structural adjustments in economic development will determine the role of water–energy–food nexus in environmental sustainability.

Traditionally water, energy and food resources are governed in many countries by separate sets of laws, rules, and institutions. However, recent studies have increasingly underlined the water–energy–food nexus approach as a framework for coherent, holistic, and integrated implementation of the Sustainable Development Goals to address fragmentations and ensure cleaner and efficient production methods in each sector. The article by Olawuyi[70] examines the legal and governance aspects of integrating and implementing the water–energy–food nexus in practice. Several legal and institutional challenges that arise with a nexus approach, such as incompatibility of water–energy–food nexus aims, limited rule linkages, institutional limitations and resource constraints are examined in order to identify the ways in which an integrative legal framework on water–energy–food can help close these gaps. The study suggests that enhanced levels of legislation and rule linkage; elaboration of common and shared principles by institutional actors in water–energy–food domains.

The main objective of the paper by Fabiani *et al.*[71] was to investigate, in a durum wheat production system in central Italy under Mediterranean conditions, the following aspects: (a) environmental sustainability of fertilization treatments through the energy inputs/outputs analysis and reduction of nitrate in water cycle; (b) agricultural system agronomic and economic performance and (c) to identify regulatory and economic instruments actually in place to promote sustainable fertilization. To describe and address the sustainability assessment of durum wheat production system we adopt the WEF nexus as conceptual framework. The findings of this paper showed that there is a great difference between the marketable yields obtained with mineral fertilization strategies and those by organic fertilizer, while considering the environmental sustainability, our results provide evidence of the significance of the reduction of energy use and the high value of renewable energies and the decreasing of non-renewable one.

The work by Smith *et al.*[72] introduces a novel triple bottom line sustainability assessment to evaluate the WEF nexus of desalination for agriculture. Falling technology costs and rising water scarcity worldwide make desalination an increasingly attractive proposition, and agriculture is one of the main sectors grappling with its potential impacts. To explore this issue, authors combine a wide range of primary and secondary environmental, economic, and social data with a triple bottom line/WEF nexus analysis, to demonstrate both the holistic sustainability impacts of desalination for agriculture, and the multi-sectoral policy environment within which desalination is adopted.

In the work of Fouladi *et al.*[73] a representation of the WEF nexus is developed to capture the trade-offs and synergies between the dimensions of sustainability within an industrial park. A unique systems approach based on thermodynamics is developed to optimize the nexus and improve resource efficiency. In this study, emphasis is placed on capturing the synergistic potential of the biomass utilization of the food sector. The results indicate that the global warming potential in the best performance scenario decreases by approximately 30%, while the exergetic efficiency of the system increases by 28%.

WEF nexus sustainability is essential for ensuring resource security and high-quality socioeconomic development. However, the existing relevant research not only lacks indicators reflecting the concept of nexus, but also the evaluation methods are usually based on constant weights and the evaluation scale is mainly at the national level. To address these issues, the paper by Qian & Liang[74] develops a comprehensive evaluation system that considers explicit linkage indicators and uses a variable weighted improved evaluation model to assess WEF nexus sustainability at the provincial level in China, thereby enriching existing research and guiding water–energy–food resource management. The results show that the national water–energy–food nexus sustainability index improved in 2008–2018, primarily because of WEF sustainable utilization state, and response subsystem rapidly turning from a shortcoming to a driving force.

The proposed framework by Yue *et al.*[75] is capable of balancing benefit efficiency and allocation equity using social welfare function, reconciling conflicting targets among socioeconomic, resource, and eco-environmental spheres and generating sustainable water and land resources allocation strategies considering complex and uncertain environment. Flexible water and land resources allocation schemes among different sectors, crops, and periods were generated, as well as managerial insights into what efforts should be done were provided for decision-makers. After optimization, efficiency-equity trade-off was balanced with social welfare index. Optima results show that greenhouse gas emissions contributed majority of the total loss, which cannot be totally neutralized by carbon sequestration, causing negative eco-environmental impacts.

The work by Cansino-Loeza & Ponce-Ortega[76] presents a multi-objective optimization model for the design of a WEF system that involves the sustainable production of WEF in areas that share economic activities through the industrial, agriculture and livestock sectors. Additionally, a multi-stakeholder assessment is presented to generate a set of solutions, where different priorities are given to the stakeholders. This approach allows quantifying the level of satisfaction of each of the stakeholders. Integration of resources is addressed according to economic and environmental objectives, such as the minimization of the cost of the system, water abstraction and greenhouse gas emissions. Results show that water reuse is crucial to improve the WEF nexus sustainability. Also, it was found that the most affected sector for water scarcity is the agricultural sector. This model can be the basis for planning the WEF nexus at regional level involving different stakeholders and for determining sustainable interactions between resources.

Chamas *et al.*[77] present an optimization model for WEF nexus resource management and allocation at a regional scale. The model was successfully validated using a hypothetical case study to test its efficiency under several resource availability scenarios and different policy targets. The results enhanced the understanding of the interlinkages among the nexus sectors by demonstrating the sensitivity of the water–energy–food nexus to adopted strategies. Moreover, adopting renewable energy may cause increased demands for land, but can significantly cut CO_2 emissions. The model serves as an effective decision-making tool that enables policy makers to assess multiple WEF sources and recommends the optimum resource allocation under various policy, technology, and resource constraints.

Two phase approach to design a sustainable sugarcane-to-bioenergy supply chain network is developed by Abdali *et al.*[78] In the first phase, a hybrid Best-Worst and Combinative Distance-Based Assessment method is utilized for finding the most suitable regions for sugarcane cultivation according to climatic, ecological and social criteria. Then, a novel multi-objective mixed-integer linear programming model is formulated considering the water–energy–food-land nexus. A hybrid solution method of augmented ε-constraint and CODAS method is finally developed to solve the model. This method is utilized for obtaining Pareto solutions of several objective functions; profit, water consumption and CO_2-equivalent emissions. The results show that the sugarcane can be cultivated on the available arable land area by 98.9%.

Peña -Torres *et al.*[79] reviewed several articles addressing the management of WEF nexus systems from the point of view of optimization problems using a mathematical formulation under the concept of sustainability. They identified, based on various sustainability objective functions, five nexus categories: water–energy, water–food, energy–food, water–energy–food, and extended water–energy–food nexus. The most frequently addressed nexus in the literature, based on sustainability objective functions, corresponds to the water–energy nexus. On the other hand, the least studied nexus under the concept of sustainability are the water-food nexus and the extended WEF nexus.

Studies on the WEF nexus can play a crucial role in achieving the sustainable development goals outlined in the United Nations' Agenda 2030. The WEF nexus approach recognizes the interconnectedness of water, energy, and food systems, and understanding this interdependency is vital for addressing global sustainability challenges. By examining the WEF nexus, researchers, policy makers, practitioners, and stakeholders can gain insights into the complex relationships and interdependencies between water, energy, and food resources. This knowledge can help in identifying innovative solutions and effective strategies to promote sustainable development and achieve the SDGs.

The WEF nexus studies provide a comprehensive understanding of the role of water as a critical component within this interconnection. Water, being the most sensitive element in the WEF nexus, has a significant impact on the overall stability, cooperativity, and safety of the nexus. By analyzing water-related challenges, such as water scarcity, pollution, and access, the WEF nexus studies can inform policy makers and stakeholders on the necessary actions to take to ensure the sustainable management and use of water resources.

Furthermore, the WEF nexus studies can assist in identifying opportunities for synergy and trade-offs among water, energy, and food systems. For example, promoting water-efficient agricultural practices can not only contribute to sustainable food production but also reduce the energy requirements for irrigation. Similarly, integrating renewable energy sources into water and food production processes can enhance energy efficiency while reducing greenhouse gas emissions.

In this sense Hua *et al.*,[80] focused on the food–energy–water (FEW) nexus, specifically on water security, given its major impact on the stability, cooperation, and security of the nexus. Their study recognizes existing evaluation systems as inadequate and proposes an optimized method to assess the balance and conflict between food and energy production in terms of water use. They used the Driver–Pressure–State–Impact–Response (DPSIR) model and water footprint theory to develop this method and then applied it to a case study in 31 provinces in Mainland China from 1997 to 2016. The study revealed competitive water use among industries, resulting in unsustainability. By 2016, provinces experienced various scenarios: Industry Synergy Sustainability, Industry Synergy Unsustainability, Industry Competition Unsustainability, and Industry Competition Sustainability. Apart from Xinjiang and Jilin, the other 29 provinces demonstrated a shift towards more sustainable or synergistic scenarios. Hua *et al.*,[80] presented two solutions—market allocation and administrative measures—to transform the Industry Competition Unsustainability scenario into Industry Synergy Sustainability. This shift can help with efficient and sustainable management of food, energy, and water worldwide. The study acknowledged FEW security challenges, the inefficiency of separate policies in addressing water use conflicts in food and energy sectors, and the global problem of resource sustainability. It also highlighted that water scarcity, food crises, energy supply issues, and environmental degradation are significant hurdles to many countries' development.

The research used a coordinate axis to represent the concepts of overall and local development, as well as sustainable and unsustainable development, and identified four scenarios: Industry Synergy Sustainability (ISS), Industry Synergy Unsustainability (ISU), Industry Competition Unsustainability (ICU), and Industry Competition Sustainability (ICS) (See Fig. 4.) The results revealed varying degrees of synergy and competition across the 31 Chinese provinces between 1997 and 2016, with significant disparities in their responses. Provinces like Hebei, Jiangsu, Anhui, Jiangxi, Henan, Hunan, Guangxi, Chongqing, Sichuan, and Yunnan consistently experienced the ICU scenario. The water footprints of these provinces in 1997 underscored competitive water use issues and water unsustainability.

On the other hand, provinces like Inner Mongolia, Liaoning, Shandong, Hubei, Guizhou, Shanxi, Ningxia, and Heilongjiang transitioned from ICU to ISU, although Heilongjiang and Jilin returned to ICU by 2012 and 2013 respectively. Meanwhile, Tianjin and Shanxi stayed in the ISU scenario. Following the ICU-ICS-ISS developmental path, Zhejiang, Beijing, Fujian, and Gansu transitioned to ICS, joining Xinjiang, Shanghai, Guangdong, Hainan, Tibet, and Qinghai who were already in the ICS scenario by 1997. Most provinces, excluding Shanghai, reverted to the ICU scenario, except for Xinjiang, which failed to return to the ICS scenario. By 2016, Zhejiang transitioned to ISS,

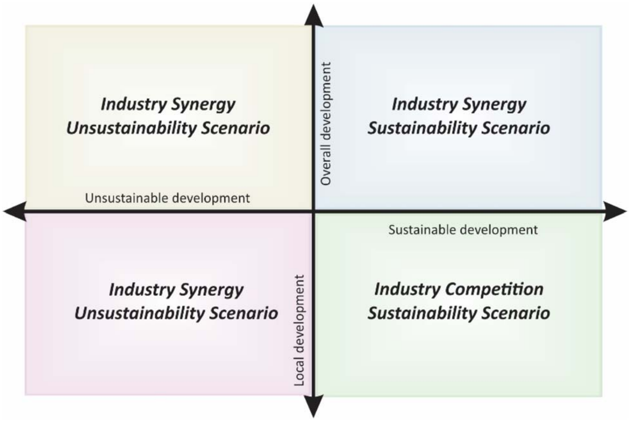

Fig. 4 Synergy and competition scenarios considered by Hua *et al.*.[81]

reducing its water footprints. However, the addition of water for ecological and domestic use disrupted the balance in Beijing and Fujian, leading them to revert to the ICU scenario.

Cansino-Loeza *et al.*[81] had proposed a mathematical model to support the 2030 Agenda for Sustainable Development, targeting economic, environmental, and social challenges in disadvantaged rural communities (DRCs). The model consisted of a Stochastic Mixed Integer Linear Program to optimize the water–energy–food nexus, ensuring sustainable resource production, meeting community utility demands, and nutritional requirements. It accounted for uncertainties in population changes and water-energy demands. The approach of the model was used to select the optimal system design from a variety of technological options, providing adaptability for the system. A Mexican community, Cochoapa el Grande, served as a case study, demonstrating the viability of the model. A significant novelty of this work lay in its approach towards poverty reduction in DRCs and nutrient provision. An innovative poverty quantification index, incorporating social indicators related to education, health, social security, housing, and food access, was introduced. On the other hand in this work, Cansino-Loeza *et al.*[81] tackled challenges faced by DRCs such as poverty, food insecurity, and limited access to water, energy, and transportation. The proposed solutions included:

- Defining a mix of crops and animal-derived foods to secure food.
- Meeting the electricity demand through the installation of solar panels or cogeneration units.
- Providing hot water through cogeneration units or solar thermal collectors *via* a thermal storage system.
- Supplying water demand through water abstraction or rainwater collectors, supplemented by water treatment plants for reuse.
- Managing municipal solid waste by separating recyclable and biodegradable waste, converting biodegradable waste into value-added chemicals and biofuels to power cogeneration systems.
- Accounting for population changes due to migration.

The optimized system was aimed at meeting water, energy, and food needs under varying population scenarios, improving DRCs' access to basic services, and reducing marginalization and poverty standards. Key uncertain parameters in the model included water and energy demand and the number of inhabitants. With limited historical data, the model used a normal distribution to generate data around a reference point, evaluating system resilience and predicting future community behavior under varying population scenarios. It merged energy and mass balance equations to fulfill electricity, water, and food requirements with the broader goal of improving living standards in these rural communities. The model encompassed uncertain parameters like water and energy needs and population size. It managed these uncertainties using a normal distribution to generate data around a benchmark. The model assessed the system's resilience and predicted community behavior under various population scenarios.

The model-based water requirement on the World Health Organization's suggestion of 20 liters per person per day. It calculated electricity needs based on the Secretary of Energy in Mexico's report, which was equivalent to 2100 kW h per person annually. It determined the monthly water and energy needs using these inputs. The model offered a choice between renewable and non-renewable energy sources depending on technical, financial, and environmental considerations. It suggested the use of solar panels and cogeneration units for power generation. These units could use either natural gas or biofuel derived from waste treatment methods, constrained by their maximum capacities. The model planned to meet water needs using water drawn from wells and collected from rainwater systems for domestic, agricultural, and livestock purposes. It also suggested using greywater and blackwater treatment plants to minimize water extraction. The hot water supply could be met using cogeneration technologies, boilers, and solar heaters.

To ensure food security, the model proposed the production of fruits, vegetables, grains, legumes, and meat to meet the minimum recommended nutrient and calorie intake.

Lastly, the model incorporated a Poverty and Marginalization Index to gauge its social impact, taking into account factors like education, access to healthcare, social security, basic housing services, and food. The goal of the model's results waste lower this index and thereby improve living conditions in these rural communities.

The results highlighted the importance of considering uncertainty in the system's design, as it significantly influenced its effectiveness. The model successfully satisfied the community's water, energy, and food demands. Notably, food production to meet recommended nutritional intake contributed significantly to the system's profitability, underlining its economic benefits.

Moreover, the study included an analysis of the Poverty and Marginalization Index calculation. The findings suggested that the implementation of the proposed approach could reduce the Poverty Index by 8% annually. This indicated that the inhabitants would likely experience an improved quality of life and progressively gain access to essential services and resources.

Understanding the status of WEF nexus, oriented to the whole process of water extraction and deployment, water consumption for crop growth, and food production output, in irrigation systems is essential for food security and resources sustainability. Based on WEF nexus quantification, combining traditional agricultural water-saving and water footprint theory, the sustainable development level of water acquisition-transfer-consumption process for pumped irrigation systems was analysed in the paper by Cui *et al.*[82] The results displays that the sustainable management can be implemented according to the unique driving factors identification of water–energy–food nexus in pumped irrigation systems. The research is conducive to the management and program for irrigated agricultural systems under the changing circumstances.

The research by David *et al.*[83] shows that the fourth industrial revolution affected the WEF nexus. The effects are: the birth of clean technologies & industrial applications, the catalyst for sustainability security of WEF nexus leveraging on life cycle thinking, enablement of technological transfer, enhancement of economic growth, and urban planning. The study concludes that the fourth industrial revolution technologies affect WEF nexus, ensuring the popularization of cleaner production strategies and processes of the resources during trade-offs and synergies. The study recommends the integration of a cleaner production concept in water, energy, and food processing. It should follow the innovation diffusion theory and technology acceptance theory when applying 4IR technologies to the nexus of water, energy, and food resources, for their sustainable security.

Peng *et al.*[84] proposed a framework that incorporated the agricultural WEF nexus into a sustainable livelihood framework, to explore agricultural sustainability. Authors then applied a partial least square–structural equation model, based on household survey data from Miyun Reservoir watershed, China, to identify the complex pathways of the impact of household farming resource endowments and livelihood diversification on agricultural sustainability. The study indicated that diversified farming achieved a better performance in the food–energy–water nexus *via* the mediating factor of farming inputs. The framework can be used to identify the relationship between household livelihoods and the food–energy–water nexus to better achieve resource security and sustainable development goals.

In summary, the sustainable design of the water–energy–food nexus is a critical research field in the search for integrated and sustainable solutions to address the interrelated challenges of resource scarcity, water security, food security and energy transition. Although significant advances have been made in this field, there are still gaps and limitations in current research. In this paper, it will explore the gaps and deficiencies identified in research on the sustainable design of the water–energy–food nexus and discuss the way forward to close these gaps and move towards sustainable and equitable management of these vital resources.

4.1 Gaps in Current Research

4.1.1 Insufficient interdisciplinarity. One of the main gaps in current research is the lack of interdisciplinary approaches. The sustainable design of the water–energy–food nexus requires the collaboration of multiple disciplines, such as engineering, ecology, economics, sociology and politics. The lack of integration and collaboration between these disciplines limits the full understanding of the interconnections and holistic solutions.

4.1.2 Technology-focused approach. Much current research is focused on the development and implementation of specific technologies to address the challenges of the water–energy–food nexus. While technologies play a crucial role, it is essential to consider social, economic and political aspects to ensure that solutions are sustainable and socially just. There is a need to broaden the focus beyond technology and incorporate multidimensional considerations into research.

4.1.3 Lack of comprehensive life cycle assessment. Another major gap is the lack of comprehensive life cycle assessment in research on sustainable nexus design. To fully understand the environmental and socioeconomic impact of the proposed solutions, it is necessary to consider the entire life cycle of the systems, from resource extraction to final disposal. This holistic assessment would make it possible to identify and mitigate potential negative impacts and optimize benefits.

4.2 Way Forward

4.2.1 Promote interdisciplinary collaboration. To bridge the interdisciplinary gap, it is essential to foster collaboration between different disciplines and promote a comprehensive approach in research on the sustainable design of the water–energy–food nexus. This can be achieved through the creation of multidisciplinary research platforms and networks, as well as the promotion of joint projects and collaboration between academic institutions and non-governmental organizations.

4.2.2 Integrating social and political aspects. It is essential to incorporate social, political and economic considerations in research on sustainable nexus design. This involves understanding power dynamics, inequalities and local needs, as well as involving communities and stakeholders in decision-making. Research must take a participatory approach and consider cultural and social contexts to ensure sustainable and equitable solutions.

4.2.3 Improving life cycle assessment. Comprehensive life cycle assessments are needed in research on the sustainable design of the water–energy–food nexus. This implies considering the environmental, social and economic impacts throughout the entire life cycle, from the production of inputs to consumption and waste management. The adoption of appropriate tools and methodologies, such as Life Cycle Assessment (LCA), can help to evaluate and compare different design options.

4.2.4 Scaling up research. To effectively address the challenges of the water–energy–food nexus, it is necessary to scale up research. In addition to studies at the system or project level, research is required at the regional and global levels to better understand interconnections and transboundary impacts. This involves collaborating with international actors and leveraging existing platforms, such as international research networks and intergovernmental organizations.

Finally, closing the gaps and advancing current research on the sustainable design of the water–energy–food nexus is critical to achieving effective and equitable management of these essential resources. Interdisciplinary collaboration, integration of social and political aspects, a comprehensive life cycle assessment and scaling up of research are key elements in the way forward. By addressing these gaps, it will be able to develop innovative and sustainable solutions that promote water, food, energy and environmental security and contribute to a more sustainable and resilient future.

Another important aspect to highlight is the analysis of trade-offs and food security. As stated by Lee *et al.*[85–87] the production, distribution, and accessibility of food may be impacted by improving the availability of water or electricity. For instance, using energy-generation techniques that need a lot of water, like hydroelectric power, can affect how much water is available for irrigation, which could have an impact on crop yields and food production. Similar choices might affect the availability or production of energy in particular areas when it comes to the distribution of water resources for agricultural use.

Developing sustainable strategies that maintain food security while maximizing water and energy resources requires an understanding of these trade-offs. Analyzing the connections across diverse industries might make it simpler to spot potential conflicts, synergies, and opportunities for integrated solutions.

Within the context of the water–energy–food nexus, it is also crucial to take into account additional elements like population expansion, climate change, and technological improvements. It is possible to increase food security while avoiding trade-offs by putting in place regulations that encourage efficient water and energy use in agriculture, adopting renewable energy sources, utilizing sustainable farming practices, and guaranteeing equitable resource distribution.

Overall, in order to create effective policies and practices that balance the requirements of these interconnected sectors and advance sustainable development, a thorough analysis of trade-offs and food security within the water–energy–food nexus is essential.

5. Challenges and opportunities of the energy–water–food nexus

Given the increasing demand for services and products due to the rapid population growth, the water, energy, and food security issues are challenges and opportunities of an ever-growing importance. As reviewed, the WEF spheres represent three resources that are intrinsically interrelated and, as such, the development of assessment tools that address interdependence is necessary, and when assessing the environmental impact of a food production system is important to understand the entire process. Therefore, a great area of opportunity for the WEF nexus is the development of assessment tools. Moreover, policies which must be administered over different timeframes have to be considered.

Short-, medium-, and long-term challenges and opportunities are:

Short term challenge: the use of renewable energy sources to help improve water and agricultural resources, to facilitate improved food security, and to help in the reduction of global environmental impact.

Medium term challenge: water resources can create a problem that leads to food insecurity in many regions of the world. Therefore, policies must be established to guarantee an adequate water supply, while at the same time seeking to increase the fertility of the land to produce only the necessary.

Long term challenge: the food-water-energy nexus must be an integrated modeling framework that builds on the issue that addresses sustainability issues at a global level.

6. Future research directions

The problem of the water–food–energy nexus has become a crucial challenge in the context of sustainability. One of the biggest challenges in the area of sustainability of the nexus problem is the scarcity of resources. Population growth and urbanization are putting increasing pressure on water, food and energy resources, leading to increased scarcity in some regions of the world. This scarcity poses a significant challenge to ensure equitable and sustainable access to clean water, nutritious food, and reliable energy. In addition, competition for limited resources is another major challenge. The use of water for agriculture and energy can conflict, especially in areas where resources are scarce. This competition creates tensions and makes integrated management of nexus resources difficult. It is necessary to develop approaches and strategies that allow an equitable and efficient distribution of resources among the different sectors.

Climate change is another significant challenge in the area of the water–food–energy nexus. Alterations in the patterns of water and energy availability, as well as in food production systems, are directly related to climate change. Extreme weather events, such as droughts and floods, negatively affect water, food and energy security, and increase the complexity of the nexus problem.

The integrated management of water, food and energy resources is a key opportunity. By taking a holistic and collaborative approach, synergies and sustainable solutions can be identified that benefit all three sectors. The integration of policies and strategies at all levels, from local to global, can generate mutual benefits and avoid unnecessary conflicts.

Resource efficiency and conservation are also important opportunities. Improving the efficiency in the use of water, energy and food can reduce the pressure on these resources. For example, the adoption of more efficient technologies in agriculture, such as drip irrigation systems or precision agriculture, can help optimize the use of water and nutrients, thus reducing environmental impact and improving productivity. Similarly, fostering energy efficiency and promoting conservation practices can contribute to the sustainability of the nexus. The development and implementation of innovative technologies can improve the management and use of nexus resources. Renewable energy, such as solar and wind power, offer a sustainable alternative to conventional energy sources and can reduce the carbon footprint of the nexus system. Likewise, desalination and water purification techniques can provide solutions to water scarcity in arid and coastal regions.

To move towards the sustainability of the water–food–energy nexus problem, it is necessary to consider some future directions. First, a comprehensive and collaborative approach to decision-making and policy implementation is required. Governments, international organizations and relevant stakeholders must collaborate to establish policies and regulatory frameworks that foster integration and collaboration between the water, food and energy sectors.

In addition, investment in research and development is essential. More research is needed to address the challenges of the nexus, including the development of more efficient and sustainable technologies, as well as understanding the impacts of climate change on the nexus system. Technological innovation will play a key role in moving towards sustainability, and collaboration between academia, industry and policy makers needs to be promoted.

Education and public awareness are crucial elements to achieve sustainable management of the water–food–energy nexus problem. The promotion of greater awareness of the importance of sustainability and the adoption of sustainable practices in the management of water, food and energy are essential. This can be achieved through campaigns of the awareness, educational programs and promotion of community participation in decision-making. To move towards the sustainability of the nexus problem, it is essential to establish integrated policies, invest in research and development, and promote education and public awareness. Only through a holistic and collaborative approach can we ensure a prosperous and sustainable future for generations to come.

7. Conclusions

This literature review examines the evolution of the concept of sustainability in the WEF nexus. We have surveyed literature spanning from 2011 to date in order to extract lessons from the policies implemented in the design of the WEF nexus with a sustainability nature. Through the different research works reviewed, the connection of the WEF spheres was shown in order to generate sustainable designs with water, and energy resources. The following can be concluded:

- Policies implemented with the proper use of WEF nexus tools, are fundamental to increase food security, energy, and water resources between regions, areas and/or countries. Achieving the concept of sustainable development.
- Adequate energy and water demand is required to meet food security. The improvement of the infrastructure will amplify economic growth while reducing environmental impact for the sake of sustainability.
- Biodiversity and/or natural resources should not be compromised to achieve sustainable designs in the WEF nexus.
- Modern indicators of environmental quality and economic growth support the solution of sustainable schemes.
- As of now, policy reforms are still needed to encourage sustainability and growth in a number of areas.

Author contributions

Conceptualization: JGSH, GCZ, CRM, funding acquisition: JGSH, GCZ, CRM methodology: JGSH, GCZ, CRM supervision: JGSH, visualization: JGSH, GCZ, CRM, writing – original draft: JGSH, GCZ, CRM, writing – review & editing: JGSH, GCZ, CRM.

Conflicts of interest

There are no conflicts to declare.

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