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Conducting water-energy-food nexus studies: what, why, and how

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The increasing pressure on resources and the persistent failure to address global malnutrition are evident challenges. A significant contributing factor is the decline in the quality of production resources, particularly water. As a result, many countries and their experts have prioritized the need to balance resource consumption. To address the research gap regarding balanced and optimal resource use, various methodologies have been developed over time, culminating in nexus studies. This study aimed to investigate the what, why, and how of conducting water-energy-food nexus (WEFN) studies. The research employed a sequential mixed-methods approach, integrating content analysis with the Analytical Network Process (ANP). The findings reveal that the objectives of WEFN studies encompass a wide range of interests, which can be systematically categorized into seven principal domains: system sustainability assessment, integration of planning and decision-making processes related to resource consumption, optimization of resource use, management of resource consumption systems, development of theoretical frameworks for the nexus, evaluation of the impacts of resource consumption, and assessment of associated risks. Notably, the results indicate that system sustainability assessment is the most critical reason for conducting WEFN studies. Furthermore, the analysis of WEFN methodologies identified simulation as the most effective technique within the Analytical Hierarchy Process (AHP) framework. In the context of the ANP technique, statistical analysis and simulation emerged as the most important methods. This research advocates for using a diagram to facilitate the selection of the optimal method for conducting a WEFN study.

Keywords Water-energy-food nexus, Analytical network process, Analytical hierarchy process, Nexus study diagram

The water-energy-food nexus (abbreviated Nexus) is an interactive approach between the three main sources of production, which was created with the aim of optimal and sustainable use of resources. The philosophy of the formation of the Nexus is the need to pay attention to the three basic resources available to humans, which are in danger of destruction due to continuous environmental changes and human manipulations. The correlation between these three important sources determines the survival of humans and the biosphere[1]. The main challenge is that the change in the spatial and temporal scales of one resource affects the other two, so Nexus must be able to recognize the conflicts created and resolve them[2]. A Nexus is a system that consists of connecting other subsystems. Therefore, the relationship between these subsystems, synergies and the effects of each part on other parts, as well as the platforms related to it should be considered[3]. The Nexus is based on productivity and integrated resource management. The infrastructures for the use and renewal of the three main sources of production need to be reconstructed and redesigned today because the production of resources is interdependent. Each part of the Nexus has unique effects, behaviors, and characteristics, so it is not possible to plan for one part to guide another part[4].

In the conducted studies and researches, different reasons for the implementation of the Nexus have been stated, which include the supply chain of the three sources of water, energy and food, the severe limitation of resources at the world level, the growing demand for the use or storage of the three sources, access to resources in terms of quantity and quality, changes in the supply and demand of production resources in human societies, the dependence of the main production resources on climate change and the need to cope with its challenges, the increase in human crises such as poverty and hunger and the provision of water and healthy food for the people, slow movement towards the approved goals of sustainable development, political conflicts and governance of the main sources of Nexus, changing lifestyles in the world, destruction of natural ecosystems to restore human ecosystems, along with the inefficiency of the old development approaches, instability in social systems due to the loss of flexibility in the face of the lack or absence of production resources, the need to ensure the security

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of production resources, integration, management, and stable governance, policymaking for balanced and sustainable development in spatial and temporal scales, and finally, resilience, adaptability and adaptability to complex conditions in human societies[5–10].

The 20th century, after World War II, was the beginning of unprecedented production using chemicals. Along with that, countries freed from war faced the crisis of explosive population growth. Providing food for this hungry and war-weary population led the developed countries or the so-called first-world countries to seek colonization and trading of other countries' resources in addition to using their resources, to combat their hunger. This trend of population growth continued until the United Nations predicted 9.6 billion people in the world by 2050. It can be said that this growing population, despite the increase in the power of technology in food production and management strategies for the use of resources, still puts a lot of pressure on resources, so due to the lack of these resources, exploitation, and extraction are excessive. Food production has caused dietary changes to occur in different regions of the world and creates a double concern for the protection of the planet[11]. The development of urbanization, economic growth, and the reduction of non-renewable resources have caused countries to put additional pressure on the few available resources to achieve a better situation and in most cases to maintain their current situation[12].

The increase in global population along with climate change has increased food insecurity in the world. The increase in food insecurity has shown itself in two forms: the number of hungry people and the number of malnourished people. As illustrated in Fig. 1, the percentage of hungry people in the world has decreased significantly from 28% in 2000 to 18.3% in 2023. Concurrently, the percentage of individuals experiencing malnutrition has also declined, dropping from approximately 12% in 2000 to around 10% in 2023. These trends highlight the progress made in addressing global hunger and malnutrition over the past two decade[13].

This slowdown in the reduction of poverty and malnutrition is primarily due to fluctuations in food production processes. Fluctuations in food production can be due to various factors, but one of the most important factors is climate change. Figure 2 shows the dollar value map of global food production and Fig. 3 shows the global climate change map. As it is clear in these figures, countries with less climate risk have produced more food in terms of value, and as a result, they will have fewer hungry people. This is because the people of these countries

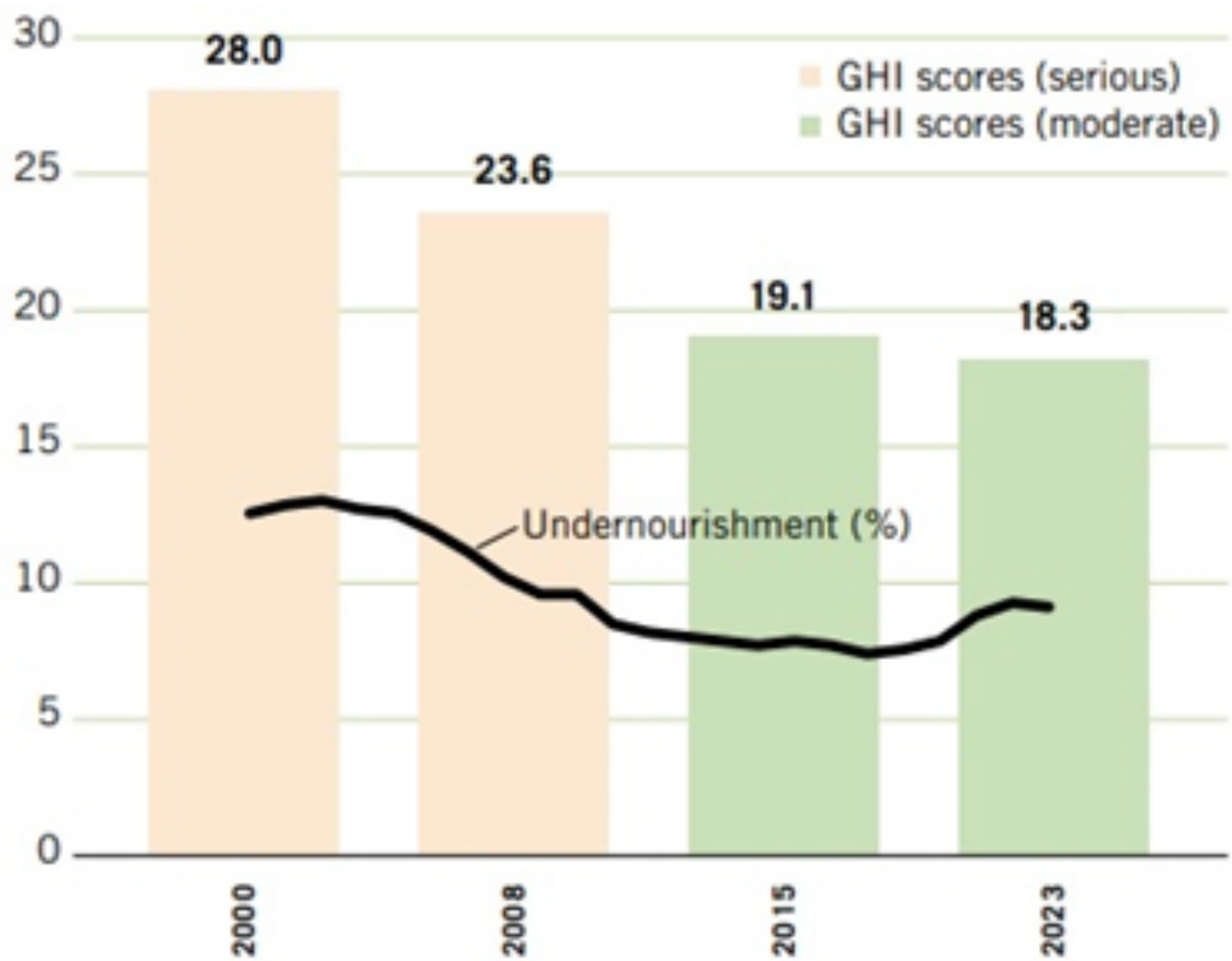

Fig. 1. World GHI scores and prevalence of undernourishment in recent decades[13].

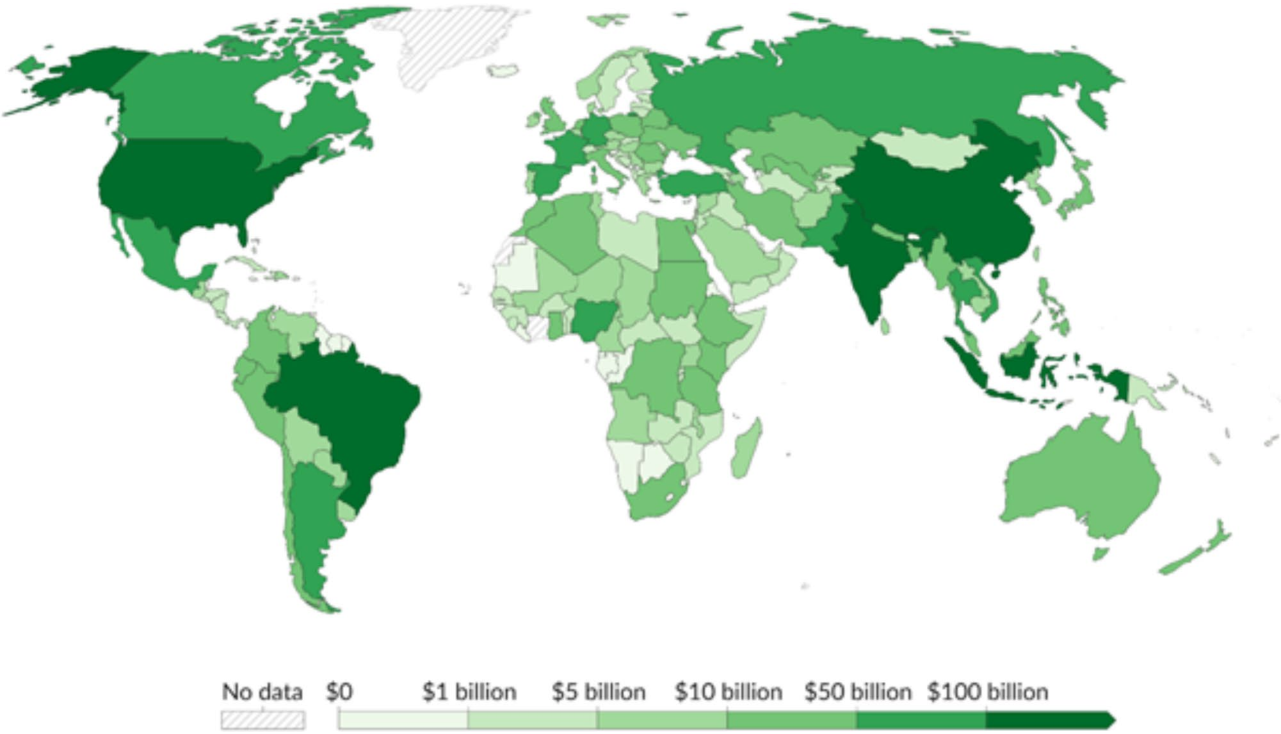

Fig. 2. World agricultural output map[14].

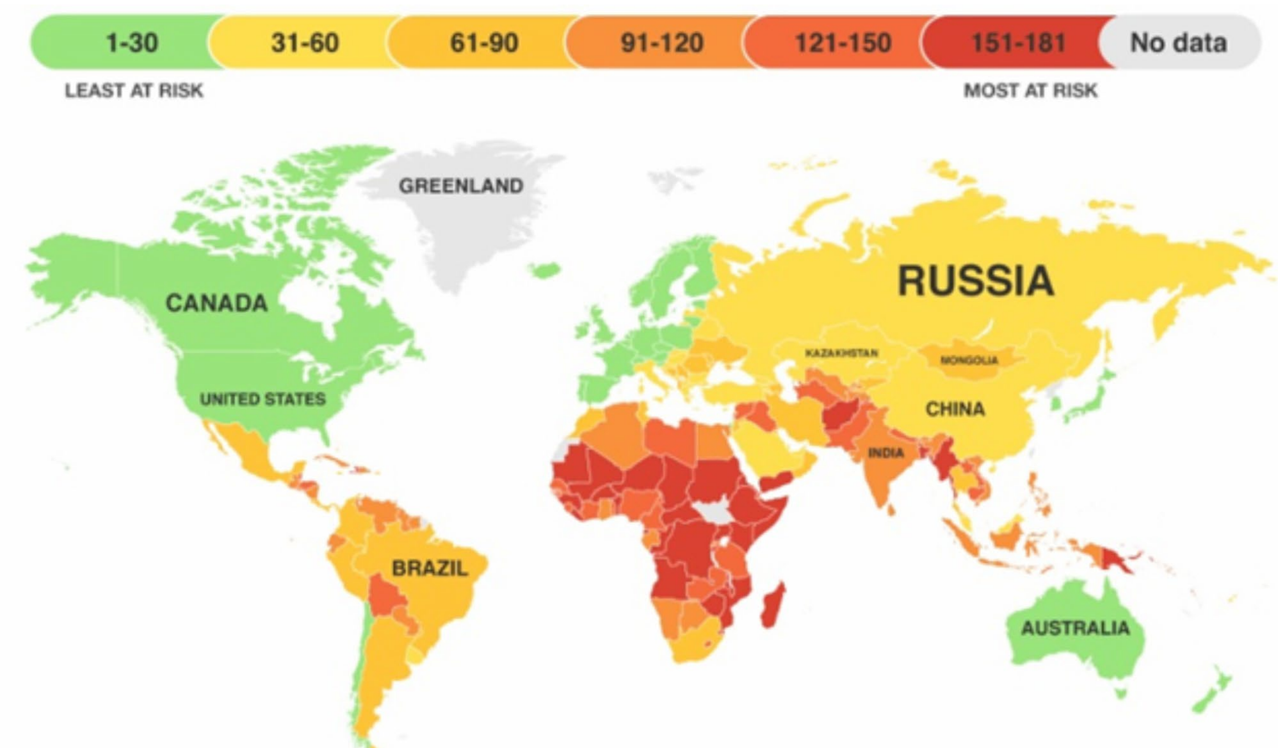

Fig. 3. World climate change map[15].

earn money by selling their food products and fulfilling their daily needs. As shown in the figures, African countries that bear more climate risk also have lower economic value of food production, and as expected, the hungriest people in the world also live on this continent.

The impact of climate change on global food production is undeniable, especially when the significant technological changes in the field of agricultural production in recent decades are considered. With the increase in the level of agricultural technologies, the increase in food production is a natural problem, but the rate of this increase in food production is not in sync with the rate of increase in the level of technology. The most important reason for this is the decreased quality of agricultural resources (water, soil, and temperature) due to climate change[16,17]. This issue has made the matter of establishing a balance between production resources to be on the agenda of many countries in recent years. By turning the balance of food production resources into a concern, the topic of nexus appeared in the research literature of the world[18,19]. Therefore, this study aims to explore the what, why, and how of the water-energy-food nexus (WEFN) and identify the most effective method for conducting such studies. The "what" aspect involves defining the WEFN across different studies, while the "why" delves into the goals and motivations behind these studies. In the "how" section, various methods used in conducting WEFN studies across different disciplines are analyzed. Ultimately, different methods for WEFN studies are prioritized using analytical network analysis (ANP). The subsequent sections of this study will provide further details on these aspects.

Technology has helped today's world move towards more prosperous and comfortable societies. Governments and countries consume more resources and energy to achieve ideal life and well-being for their people than ever before. Investing in industries dependent on natural resources such as oil is also the reason. The important point is that, in the path of progress, what is usually affected in countries, especially developing countries, is the environment[12]. Inconsistency between production resources can cause a crisis in the sustainability of the ecosystem and environment. For example, excessive use of fossil fuels causes all kinds of pollution in the environment, or excessive use of water resources for food production will reduce these resources[20]. Any pressure on the ecosystem of a region will directly affect the WEFN. For example, a drought affects food security, a decrease in rain affects water resources, and temperature changes in an ecosystem affect the production and consumption of energy resources. Climate change causes the loss of biodiversity in an ecosystem. Unexpected changes in temperature in cold regions or changes in precipitation rates in rainy regions cause damage to plants and living organisms in these regions. Also, the growth of the human population and the need to produce more food causes humans to encroach on the boundaries of the ecosystem and change the use of the ecosystem to acquire more land or water for food production, which in turn intensifies the consequences of climate change in the region[21].

The most important applications of ANP in choosing the appropriate research method in WEFN studies are: (1) determining priorities: using ANP, researchers can determine different priorities based on multiple criteria that may overlap. This is especially critical in situations where the choice of research method is influenced by various factors, (2) considering dependencies: ANP allows researchers to consider internal and external dependencies between criteria and options. This feature is very important to choose appropriate research methods that may be affected by environmental or social factors, and (3) scenario analysis: ANP allows the analysis of different scenarios, which can help decision makers to choose the best options for research. These analyzes can include evaluating the effects of changes in conditions or management policies. Research on the water-energy-food nexus underscores the crucial role of agricultural development. The direct impacts and synergies between water, energy, and food resources and grappling with major environmental effects like climate change can affect in sustainable development. Optimizing resource utilization necessitates conducting studies within a robust method and framework. Moreover, diverse approaches to these resources across various studies reveal that, without an optimal methodology, research outcomes often lack clarity and practicality. Focusing on the nexus and its regional effects, including the influence of internal factors like population growth and external factors such as climate change, has been extensively examined. However, the need for an optimal methodology to conduct comprehensive nexus studies remains pronounced, and this research aims to fill this knowledge gap.

Research Method

The method of conducting this research was a sequential mixed research method. The different stages of this research are shown in Fig. 4. In the first phase, researches were analyzed from the point of view of what, why, and how to conduct WEFN studies, and it was used to develop a decision tree. To perform this part of the research, content analysis was used. In the second stage, participants in the research were selected. In the third phase, the decision tree was developed, and in the fourth phase of the research, the Analytical Network Analysis (ANP) method was used to determine the relative importance of alternatives and criteria.

Step 1: literature review and content analysis

In the field of selecting the articles to be studied, articles were considered that mentioned WEFN in their title. Due to the time limit of the research, about 100 articles were selected. Content analysis is one of the documentary methods that deals with the systematic, objective, quantitative, and generalizable examination of communication messages. This method is considered a concealer in the classification of methods, and it is used to check the obvious content of the messages in a text, as a result, it does not enter into the interpretation and semiotics of the message content. Content analysis is a convenient way to answer questions about the content of a message. Although in the early approaches, it was claimed that content analysis could deal with the characteristics of the author and the impact on the audience in addition to the message content, today, the latter two functions are considered possible only in field and document integration methods. Referring to this topic, only objective messages were considered. In the context of examining the nature of the WEFN, different dimensions of the WEFN were reviewed and presented in different articles. In the context of identifying the reason for conducting

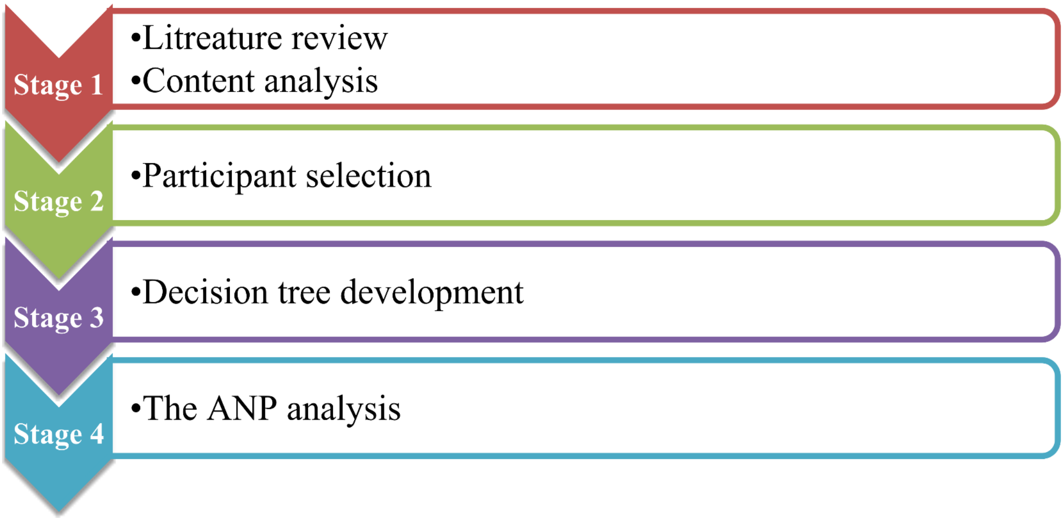

Fig. 4. Research Stages.

Groups of participants	No.	Reasons for selection
Water experts	3	To represent the view of their discipline in Iran
Food experts	3	Logical thinking ability
Energy experts	3	Capable for pairwise comparison
	3	Key informants
		Working in different dimensions of expertise
Nexus experts		Working at different organizational levels

Table 1. Descriptions of the research participants.

the research, referring to the purpose of the research, if mentioned, the reasons why (and not the interpretation according to the opinion of this study authors) can be extracted. In the investigation of how using the "Research method" section of the studied articles in the why section, the hows were determined.

Step 2: selection of participants

In terms of selecting participants in the research, 3 experts in the field of water, 3 experts in the field of energy, 3 experts in the field of food, and 3 experts in the field of nexus studies were selected. The selection characteristics of these experts can be seen in Table 1. The criteria for selecting the respondents were representativeness of the views of Iranian experts in their field, having the power of logical thinking, having the ability to complete a pairwise interview, being a key informant, working in different dimensions of their expertise, and working at different organizational levels.

Step 3: develop the decision tree

To determine the relative importance of the nexus's why and how, the decision tree of this research was developed based on the findings of stage 1. A decision tree is an algorithm that is widely used in classification and prediction problems. In this algorithm, for each sample of the input data, a decision tree is built, which hierarchically includes the overall goal, criteria, and alternatives. In this research, the criteria consist of the reasons for conducting WEFN studies, and the objectives are how to achieve these reasons (or different methods of conducting WEFN studies).

Step 4: ANP analysis

The ANP method is one of the multi-criteria decision-making methods (MCDM), which is similar to the AHP method, but in which criteria or sub-criteria or alternatives have dependencies or relationships. The AHP method can be considered a special mode of the ANP technique. If there is a problem in which the criteria, sub-criteria, or alternatives have internal relationships with each other, this type of problem cannot be solved through the AHP method because the problem will leave the hierarchical state and create a network state. The process of network analysis provides a comprehensive and powerful method for making accurate decisions using empirical information or personal judgments available to each decision-maker and providing a structure for organizing different criteria and evaluating the importance and preference of each of them over alternatives makes the decision-making process easier. ANP is implemented using Super Decisions software and is applied to a variety of decisions including marketing, medical, political, military, social, forecasting, and many others[22]. The ANP method and its application in various fields are well documented in the operational research literature.

The purpose of using this method was to compare the whys (as criteria) and the hows (as indicators) in the first step and determine the more important method by referring to the purpose of the study. In the second step, which transforms the process from AHP to ANP, the goal is to determine which method can serve as a better complement when performing a method to overlap with that method. This issue was chosen because, in addition to the criteria, alternatives are also compared with each other from the point of view of alignment and complementarity with other alternatives, because many researchers seek to determine a research process for themselves. Therefore, for researchers who are interested in the topic of nexus, it is better to rely on methods that the data and findings of that method can be used in future studies that may be done with other methods.

It is important to note that the Ethical Committee of Tarbiat Modares University granted approval for the research, and all aspects of the study were conducted according to the relevant guidelines and regulations. Additionally, adherence to the Declaration of Helsinki was ensured throughout the research process.

Findings

What is the WEF nexus?

Water-energy-food nexus which is called "WEFN" for short in this research, is an adaptive approach that increases the resilience of energy, water, and food resources in the conditions of climate change and population growth[23]. The conceptual WEFN is local, national, territorial, and extra-territorial and in it, synergies and exchanges take place between water, food, and energy resources and the security of these resources for sustainable production, development, and environmental protection. In the nexus, a balance has been made for synergizing resources and correct and sufficient exchanges between resources, and the result is cost-effective production while using few resources and on the path of sustainable development. Nexus from the terminological perspective is an emerging concept focusing on the link between social sciences and natural sciences. By understanding the nexus between water, energy, and food resources, the nexus is trying to reach a unified concept and be able to deal with the problems of today's world. In addition, the concept of nexus is directly or indirectly affected by issues such as climate change, population growth, or human damages such as increased land use change, war, social issues, urbanization, etc[11].

In the definition of the nexus, two categories can be mentioned: (1) The first category, which refers to the interaction between the three main poles, deals more with the development of concepts that depend on their connection and relationships. For example, at the border between energy and water and where water is used for energy or energy for water, the definition of the nexus and its classification is formed. In the food dimension, the concepts begin where the border of food production and energy and water use are intertwined. In this category, the interactions and subsystems related to each section and the general characteristics of the WEFN are also taken into consideration. (2) The second category, which is used more in research, looks at the concept of connection as a paradigm of analysis and quantification of concepts and relationships between the three main dimensions. This category ends with smaller definitions such as the approach of man and nature or the integrated management of natural resources through WEFN. In this category, researchers focus on the nature of production, use, and distribution of resources, along with how these resource links evolve and reach a state of sustainability in the environment and ecosystem, and use analytical tools, governance theories, and the like[20].

In 2011, at the World Nexus Conference in Bonn, Germany, for the first time, concepts related to nexus and its relationship with sustainability were discussed. In the initial concepts of the WEFN, the direction of the studies was more toward systematic decision-making in critical conditions of water, energy, and food resources[23,24]. Awareness of the double pressure on water, energy, and food resources and the threat it had created for sustainable development in the countries of the world led to the establishment of this conference because these pressures caused irreparable damage to the body of sustainable development[25]. The concepts of water, food, and energy in the nexus paradigm both individually and continuously examine the dimensions of sustainable development and resource protection. The continuity of these three concepts is based on the three flows of "access, availability, and use". Access refers to that aspect of resources in which people can purchase, produce, or be assisted in the process of acquiring that concept. Availability refers to the processing and distribution of food and renewable energy, and finally, the use of resources means valuable and regulated consumption[12,20]. The nexus has two distinct dimensions, inter-disciplinary and supra-disciplinary. The first dimension deals with the link between water, food, and energy and the relationships between these dimensions, and in the second dimension, the relationships between beneficiaries, different privileged and disadvantaged groups, governance, decision-making and creative thinking, and in general non-technical issues in the field of water, food, and energy[24].

Water-energy-food nexus dimension

Water system (first dimension): Water resources have been the place of gathering and formation of human communities, and more than that, the place of concentration and expansion of civilization. Water systems consider all issues and challenges related to human drinking water, domestic use, livestock consumption, plant production and garden construction, industrial use, and energy production. The connection of water is much more important than the other two dimensions, namely food, and energy, because the existence of water resources largely leads to the existence, production, and sustainability of food and energy resources. In the past years, due to the excessive use of water resources, especially underground reserves in different parts of the world, problems such as land subsidence, the change and dominance of invasive alternatives, the destruction of ecosystems and biodiversity, and the destruction of natural ecosystems by humans have arisen. Several solutions are used to prevent the collapse and disintegration of water systems in different regions of the world. The first is the development of water extraction, transfer, and recycling infrastructures, in which, through the design of a comprehensive and extensive system in economic, social, and political dimensions, efforts are made to prevent water wastage and inappropriate use and to introduce new technologies of use and recycling and add water into the natural cycle. Second, there is the issue of water governance, which, in short, according to the historical background and the role of water in human civilization, all traditional and modern water management solutions in a region are considered, and the way water is used is managed with the participation of the people who are its beneficiaries[11].

Energy system (second dimension): The evolution and sustainability of human societies depend on energy. After the industrial revolution of the 19th century, the issue of energy extraction and production is as much a priority for societies as food production. The energy system deals with issues such as energy production, access to raw resources, energy production from renewable sources, energy sales and trading, energy policy, energy resource governance, energy consumers and traders, and so on. Today's energy crisis is the product of excessive use of non-renewable energy sources such as fossil fuels and wood resources such as forests so until 2018, more than a third of the world's population did not have access to suitable and sufficient energy sources.

On the other hand, the use of fossil fuel resources in less developed societies has caused the climate of these regions and, as a result, the climate of the whole world to be in crisis. The ever-increasing need for energy resources comes from the increase in the world's population, and in the meantime, the development of new technologies that are mainly dependent on the production and consumption of electrical energy also fuels this problem[11].

Food system (third dimension): A food system of production, production method, distribution method, consumption, used inputs, transportation, labor force, policies related to food production, type of diet of the studied community, local ecosystem and regional climate, consumers and links are formed between these components. Food systems are directly affected by the increase in population its growth rate, and climate change. Findings have shown that in the early 20th century and the 1930s, the world population was about 2 billion people. This population reached three billion people after nearly 30 years, but it took only 50 years until around 2011 to reach more than double and nearly seven billion people, so with this unprecedented growth and due to the significant growth of technology, food systems cannot meet the needs of human society. This decrease in the power of food systems in the 20th century was accompanied by the increase in the use of chemicals and the change in the use of natural ecosystems for food production. The result of these actions was the pollution of water, soil, and air and the destruction of biodiversity[11].

Why nexus?

In this sections, the reason for carrying out WEFN studies was analyzed. To analyze this issue, the studies conducted on the connection of water were examined. The results showed that these studies can be classified into seven groups. These categories included system sustainability assessment, integrating planning and decision-making processes on resources consumption, resources consumption optimization, resources consumption system's management, developing nexus theoretical foundations, resources consumption impacts assessment, and resources consumption risks evaluation (Table 2). As can be seen in Table 2, among the studies conducted, the most common reason for conducting the WEFN studies was to determine the system sustainability assessment (with 21 studies), and the least reason for conducting these studies was to evaluate the risks caused by the consumption of resources (9 studies).

How to nexus?

After examining why WEFN studies were conducted, how these studies were conducted were analyzed and the findings of this section are presented in Table 3. As seen, trend analysis, meta-analysis, simulation (with different simulation methods), survey, content analysis, input-output analysis, economic analysis, multi-criteria decision-making, statistical analysis, life cycle analysis (LCA), ecological network analysis, experiment, and optimization modeling has been various methods used in the study of WEFN. Among these methods, simulation (31 cases) has the highest amount of use, and trend analysis, meta-analysis and experiment methods (1 case) have the lowest amount of use.

Why WEF nexus	References
Resources consumption risks evaluation (9 studies)	26–33
System sustainability assessment (21 studies)	2,34–53
Resources consumption system's management (13 studies)	54–66
Integrating planning and decision-making process on resource consumption (18 studies)	57,67–83
Resources consumption optimization (17 studies)	49,84–99
Resources consumption impacts assessment (18 studies)	100–117
Developing nexus theoretical foundations (13 studies)	118–130

Table 2. Classification of reasons for using WEFNs.

How to WEFN	References
Trend analysis (1 study)	131
Meta synthesizes (1 study)	132
Simulation (31 studies)	27,30,31,34,49,55,62,64,65,77–79,82,87,95,96,98,101,103,104,109–111,127–129,133–137
Survey (8 studies)	35,58,67,74,118,138–140
Content analysis (5 studies)	26,39,141–143
Input-output analysis (5 studies)	84,112,120,144,145
Economic analysis (3 studies)	36,54,146
Multi-criteria decision-making (6 studies)	33,75,106,113,126,147
Statistical analysis (5 studies)	28,35,37,146,148
Life cycle analysis (LCA) (4 studies)	29,41,52,56
Ecological network analysis (2 studies)	117,149
Experiment (1 study)	61
Optimization modeling (10 studies)	25,38,45,60,80,93,94,100,123,124

Table 3. Classification of how to conduct WEFN studies.

Developing decision tree

Referring to the findings of why and how to perform WEFN, the research decision tree was developed. The purpose of developing this tree was to choose a better way to conduct the WEFN research (Fig. 5). In this tree, the reasons for carrying out WEFN studies (system sustainability assessment, integrating planning and decision-making process on resources consumption, resources consumption optimization, resources consumption system's management, developing nexus theoretical foundations, resources consumption impacts assessment, and resources consumption risks evaluation) were chosen as criteria and how to conduct these studies (simulation, survey, content analysis, input-output analysis, MCDM, statistical analysis, LCA, and optimization). It should be noted that in the selection of alternatives, the methods that have been used the most were chosen as alternatives. Then, referring to the decision tree, a pairwise comparison questionnaire was compiled and the participants were interviewed face-to-face. There were 3 questions in this questionnaire:

1. Pairwise comparison of criteria using the purpose of the research: referring to the purpose of the research, in conducting WEFN studies how much more important is the case of ……… than the case of ………?
2. Pairwise comparison of alternatives using criteria: in conducting a WEFN study with the ……… purpose, how much more important is the ……… method than the ……… method?
3. Pairwise comparison of alternatives using alternatives: in conducting a WEFN study with the ……… method, how much more important is the ……… method than the ……… method?

ANP analysis

Criteria comparison

Comparing the criteria based on the research objective (Fig. 6) showed that the criteria of system sustainability assessment, integrating planning and decision-making process on resources consumption, resources consumption optimization, resources consumption system's management, developing nexus theoretical foundations, resources consumption impacts assessment, and resources consumption risks evaluation with weights of 0.248, 0.221, 0.146, 0.131, 0.100, 0. and 0.063 respectively, are placed in the sequence of relative importance of why to conduct WEFN studies. The inconsistency index of this pairwise comparison, which according to the Super Decision software developers should be less than 0.1, is 0.0242, which indicates a rational comparison of the criteria with each other. As the findings in Fig. 6 show, WEFN studies that seek system sustainability are more important to conduct than other studies. Of course, it should be noted that all WEFN studies emphasize the available resources and their evaluation because the limitation of resources has been the most important reason for conducting WEFN studies.

Alternatives comparison based on criteria

In the next step, the relative importance of the researched alternatives (methods of conducting WEFN studies) was compared with each other according to the criteria (reasons for conducting WEFN studies) and the results were shown in Table 4; Figs. 7, 8, 9, 10, 11, 12 and 13. As can be seen, based on the developing nexus theoretical foundation criteria, content analysis, MCDM, and simulation methods have more relative importance compared to other methods (with an inconsistency index of 0.0223) (Fig. 7). Of course, according to the nature of the

Fig. 5. Decision tree to choose a better method for WFE nexus research.

studies that seek the theoretical development of a subject, it is natural to be placed in this relative importance. Because these studies mostly look for what variables are used or can be used in a subject and refer to the researcher's intended framework, which one has more relative importance and supports the research's theoretical hypotheses?

Based on the criteria of integrating planning and decision-making processes on resource consumption, and resources consumption impacts assessment, the methods of simulation, optimization, and input-output analysis have more relative importance compared to other methods (respectively with the inconsistency index of 0.0127 and 0.0092) (Figs. 9 and 10). Referring to the nature of the planning and decision-making process, the use of methods that lead to a judgmental statement[150] or the selection of resources will be prioritized.

Based on the criteria of resource consumption optimization criteria, optimization, simulation, and input-output analysis methods have more relative importance compared to other methods (with an inconsistency index of 0.0114) (Fig. 11). Also, based on the criteria of resources consumption risk evaluation criteria, simulation, statistical analysis, and survey methods have more relative importance compared to other methods (with an inconsistency index of 0.0461) (Fig. 12). This issue is mostly due to the nature of risk analysis, which requires a comprehensive review and consideration of various possibilities.

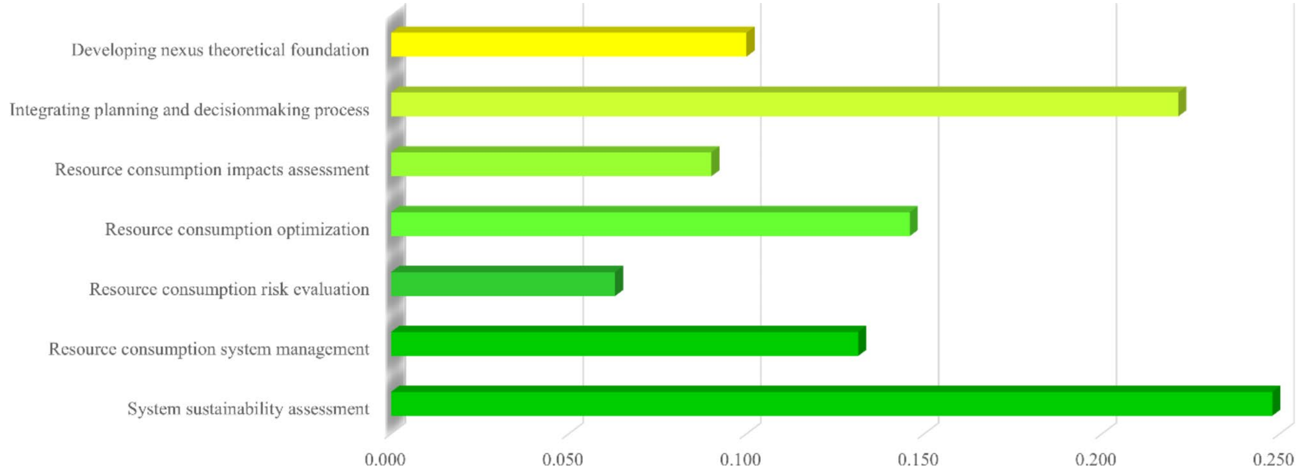

Fig. 6. Compare criteria based on the main goal.

Alternatives	Criteria						
	Developing a nexus theoretical foundation	Integrating planning and resource consumption	Resources consumption impacts assessment	Resources consumption optimization	Resources consumption risk evaluation	Resources consumption system management	System sustainability assessment
Content analysis	0.206	0.060	0.075	0.077	0.075	0.071	0.065
Input-output analysis	0.089	0.136	0.132	0.161	0.059	0.126	0.151
LCA	0.098	0.115	0.228	0.107	0.127	0.071	0.078
MCDM	0.183	0.136	0.066	0.088	0.087	0.126	0.116
Optimization	0.102	0.136	0.132	0.245	0.121	0.153	0.178
Simulation	0.143	0.244	0.219	0.161	0.201	0.234	0.214
Statistical analysis	0.089	0.085	0.071	0.077	0.192	0.091	0.090
Survey	0.089	0.085	0.079	0.083	0.138	0.128	0.108
Inconsistency index	0.0223	0.0127	0.0092	0.0114	0.0461	0.0141	0.0189

Table 4. Compare alternatives based on criteria.

Based on the resource consumption system's management criteria, simulation, and optimization methods have more relative importance compared to other methods (with an inconsistency index of 0.0141) (Fig. 13). In the end, the comparison of alternatives based on the system sustainability assessment criteria showed that the methods of simulation, optimization, and input-output analysis have more relative importance compared to other methods (with an inconsistency index of 0.0189) (Figs. 14, 15, 16, 17, 18, 19, 20 and 21).

Alternatives comparison based on alternatives

In the next step, the relative importance of the investigated alternatives (methods of conducting WEFN studies) was compared with other alternatives (complementarity for other methods in conducting interdisciplinary research), and the results were shown in Table 5; Figs. 14, 15, 16, 17, 18, 19, 20 and 21. As can be seen, based on complementarity for the content analysis method, statistical analysis, MCDM, and survey methods have more relative importance compared to other methods (with an inconsistency index of 0.0139) (Fig. 14). Considering the qualitative nature of this research, which is the analysis of previous studies in a field, understanding the statistical relationship of studies and variables to each other, prioritizing variables, and re-examining them in society can be a better complement to this method than other methods that are more based on mathematical equations.

As can be seen, based on complementarity for the input-output analysis method, simulation, optimization, and LCA methods have more relative importance compared to other methods (with an inconsistency index of 0.0226) (Fig. 15). Considering that this method is more about analyzing the input and output of the system in a certain period and drawing conclusions from the current situation. From this point of view, these three methods can be a better supplement compared to others due to their nature. This situation of the relative importance of complementarity for optimization is also repeated (with the inconsistency rate index of 0.0431) (Fig. 19).

Based on the complementarity of the LCA method, input-output analysis, content analysis, and simulation methods have more relative importance compared to other methods (with an inconsistency index of 0.0374) (Fig. 16). The presence of content analysis in the second stage of the LCA process, as well as the analysis of

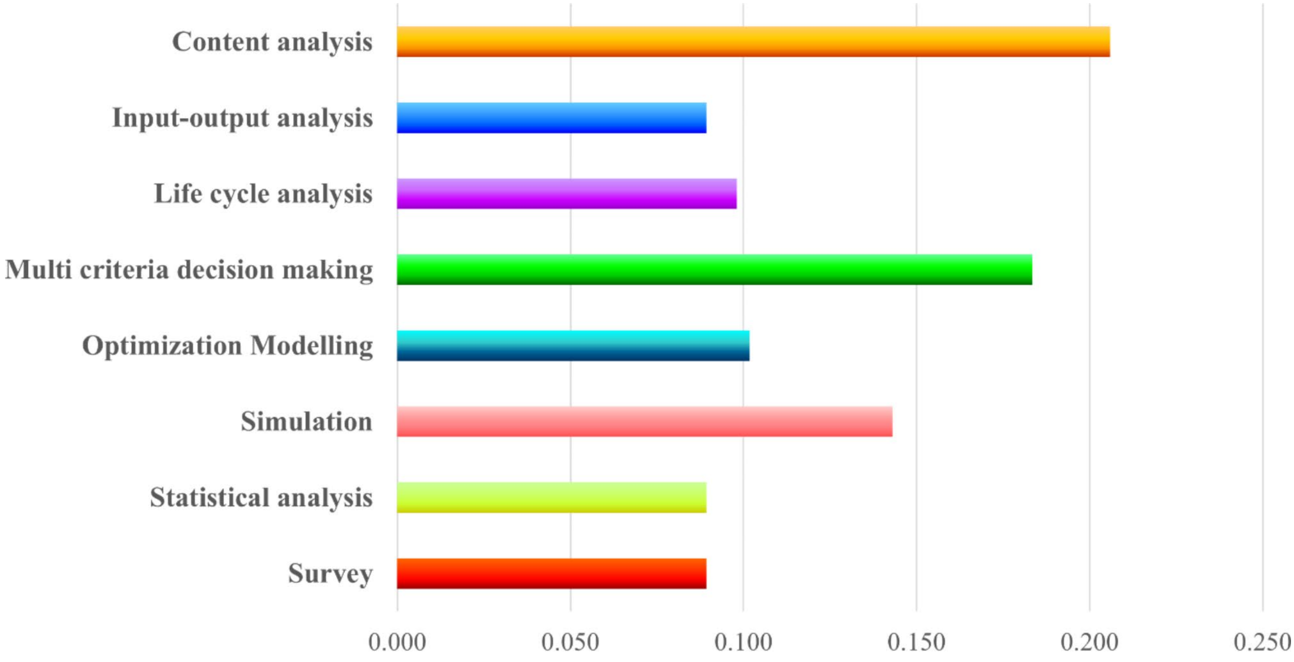

Fig. 7. Compare alternatives based on developing a nexus theoretical foundation.

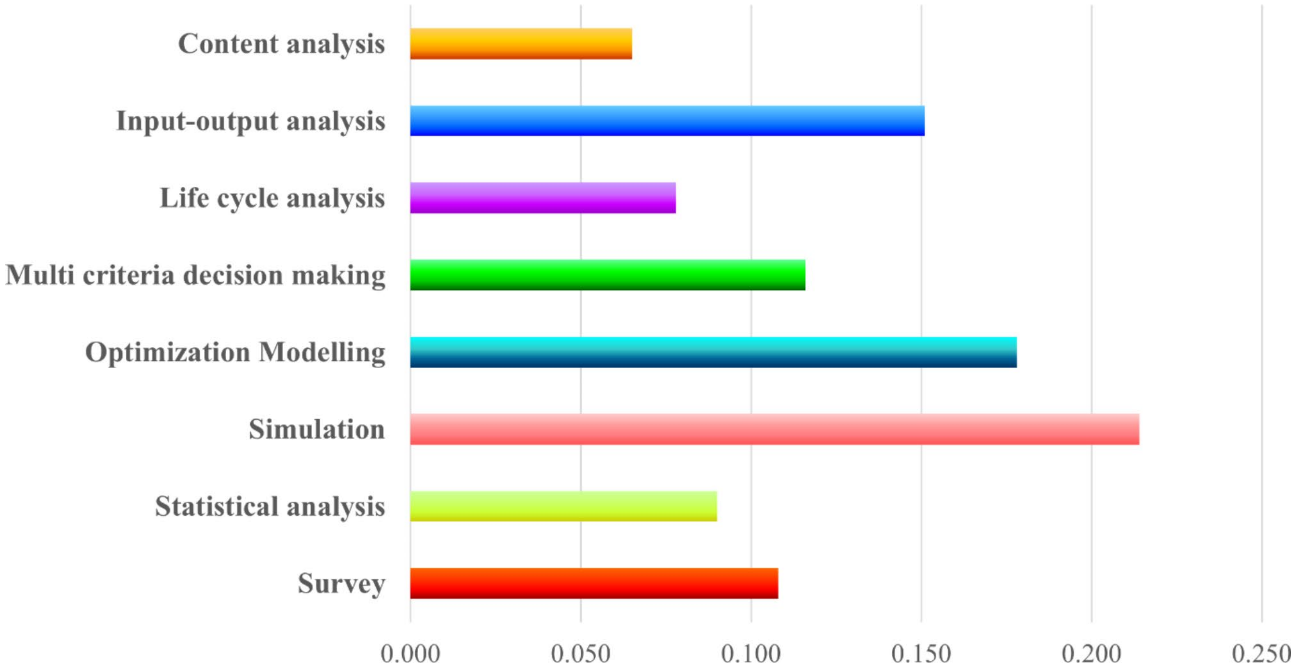

Fig. 8. Compare alternatives based on system sustainability assessment.

different libraries for the best estimation of the effects, can be a good supplement for this method and increase the quality of the studies conducted with this method.

Based on the complementarity of the MCDM method, the simulation and content analysis methods have more relative importance compared to other methods (with an inconsistency index of 0.0062) (Fig. 17). Because content analysis can be a suitable supplement for this method in the decision tree development stage. Also, the simulation can apply the findings of this method in long-term studies and can confirm the findings of this prioritization. Based on complementarity for the simulation method, statistical analysis, and survey methods have more relative importance compared to other methods (with an inconsistency index of 0.0254) (Fig. 18). The most important reason for this issue is the role of statistical analysis in determining the relationships between research variables and the role of surveys in collecting relevant data.

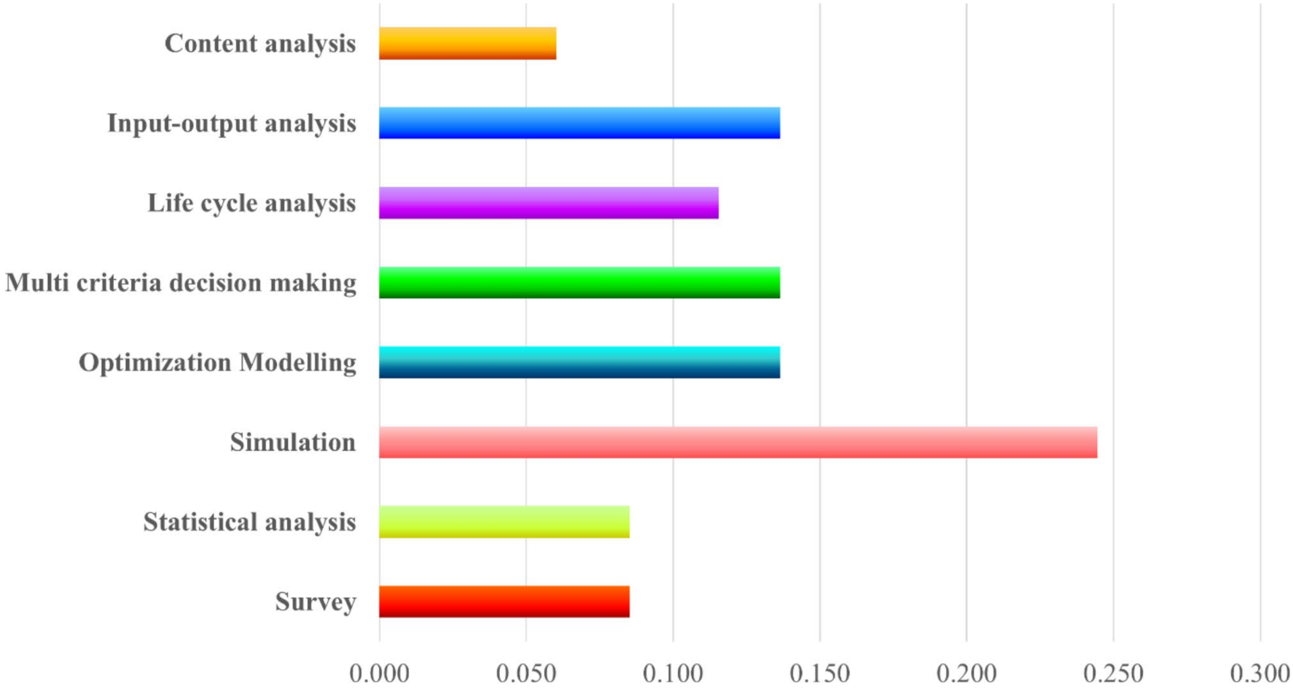

Fig. 9. Compare alternatives based on integrating planning and decision-making processes on resource consumption.

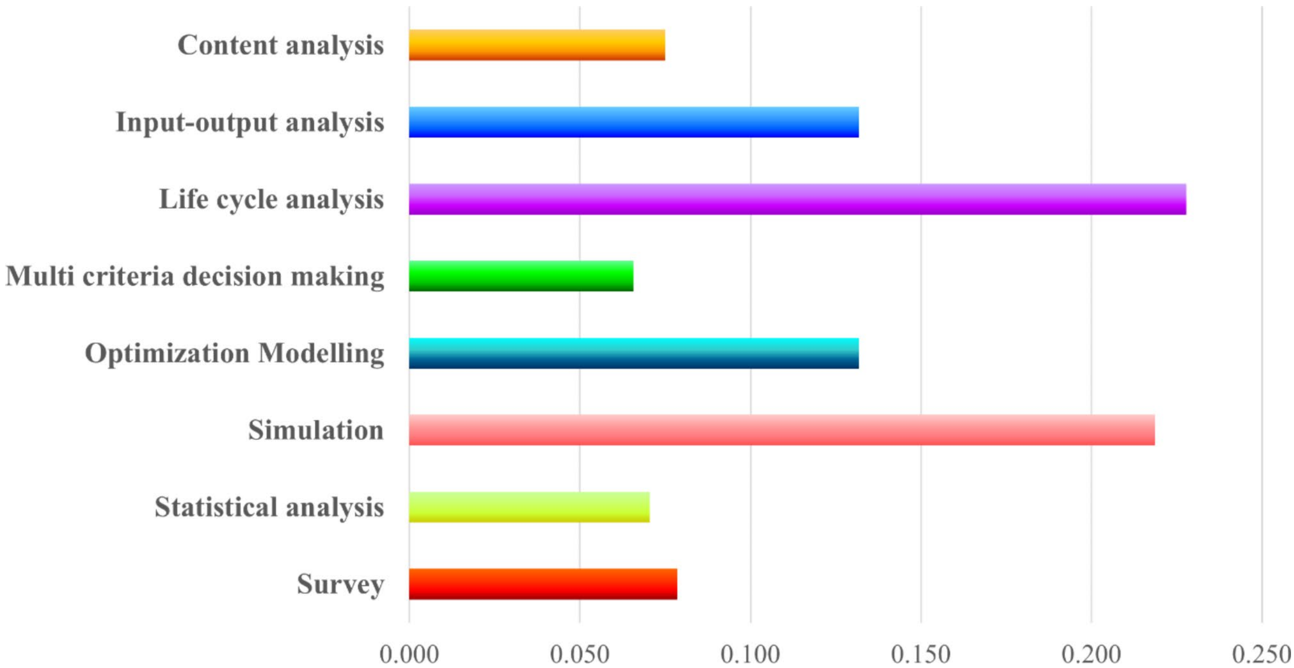

Fig. 10. Compare alternatives based on resource consumption impact assessment.

Based on complementarity for the statistical analysis method, content analysis, and survey methods have more relative importance compared to other methods (with an inconsistency index of 0.0062) (Fig. 20). Based on the complementarity of the survey method, statistical analysis, simulation, and content analysis methods have more relative importance compared to other methods (with an inconsistency index of 0.0223) (Fig. 21). The most important reason for this is that the method of content analysis helps to articulate the conceptual framework and theoretical foundations of survey studies. On the other hand, simulation and statistical analysis make it possible to generalize and create scenarios in the findings of survey studies.

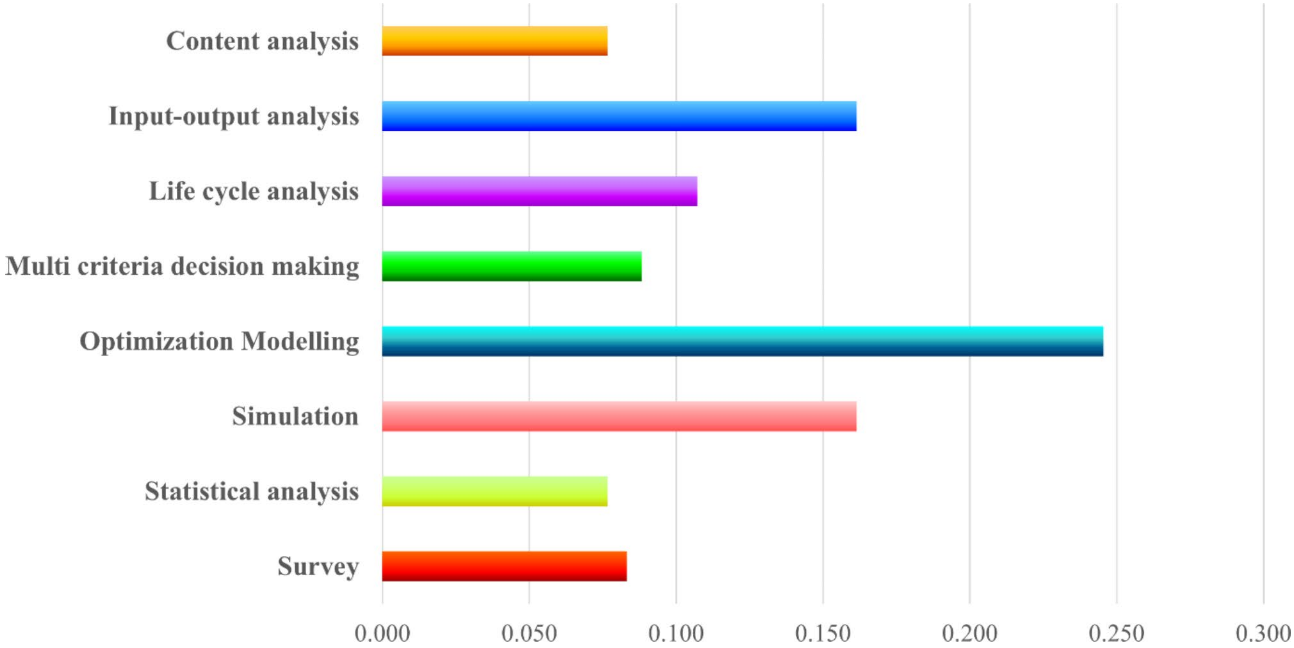

Fig. 11. Compare alternatives based on resource consumption optimization.

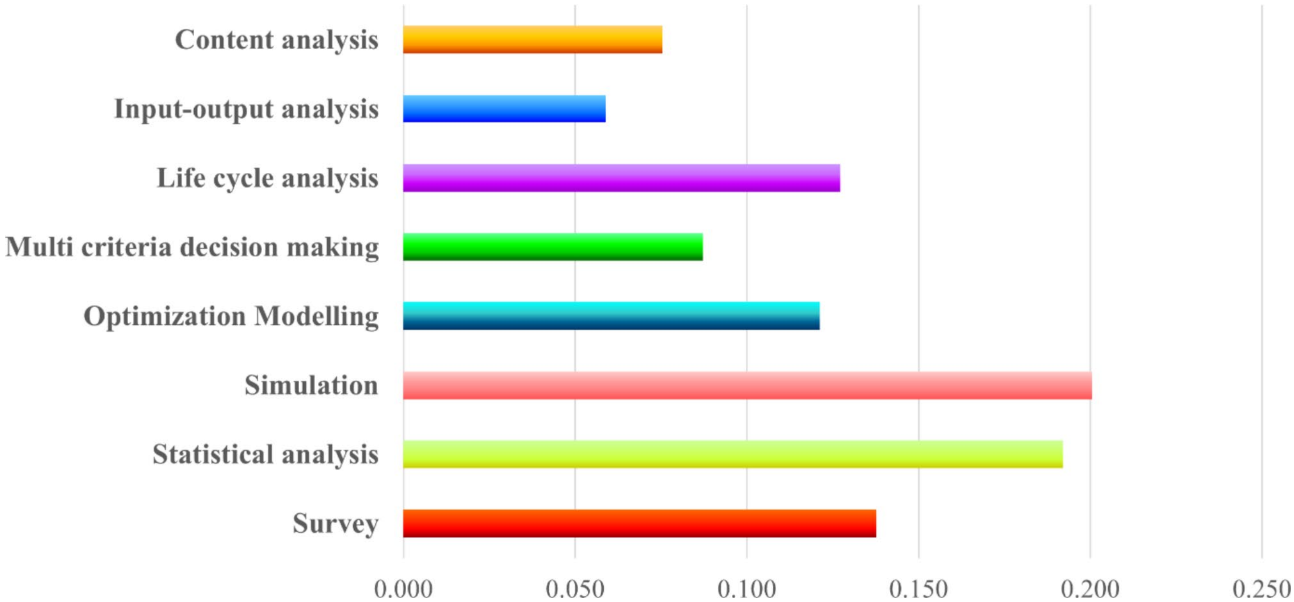

Fig. 12. Compare alternatives based on resource consumption risk evaluation.

Synthesis of alternatives

The synthesis of alternatives was done and its results for two modes are shown in Figs. 22 and 23. In the first mode, the findings were shown in the form of AHP analysis (Fig. 22). In this case, the alternatives were compared with each other only according to the criteria. The findings of this mode showed that simulation methods (normalized coefficient is equal to 0.208), optimization (normalized coefficient is equal to 0.160), input-output analysis (normalized coefficient is equal to 0.132), MCDM (normalized coefficient is equal to 0.118), LCA (normalized coefficient is equal to 0.108), survey (normalized coefficient is equal to 0.099), statistical analysis (normalized coefficient is equal to 0.092), and content analysis (normalized coefficient is equal to 0.082) are in the hierarchy of relative importance. But the important question in this context is how much these methods can help other WEFN studies and other methods. Or to put it more simply, complete them?

The answer to this question lies in the second mode and performing ANP analysis (Fig. 23). In this mode, the alternatives were compared with each other not only regarding criteria but also regarding complementarity for

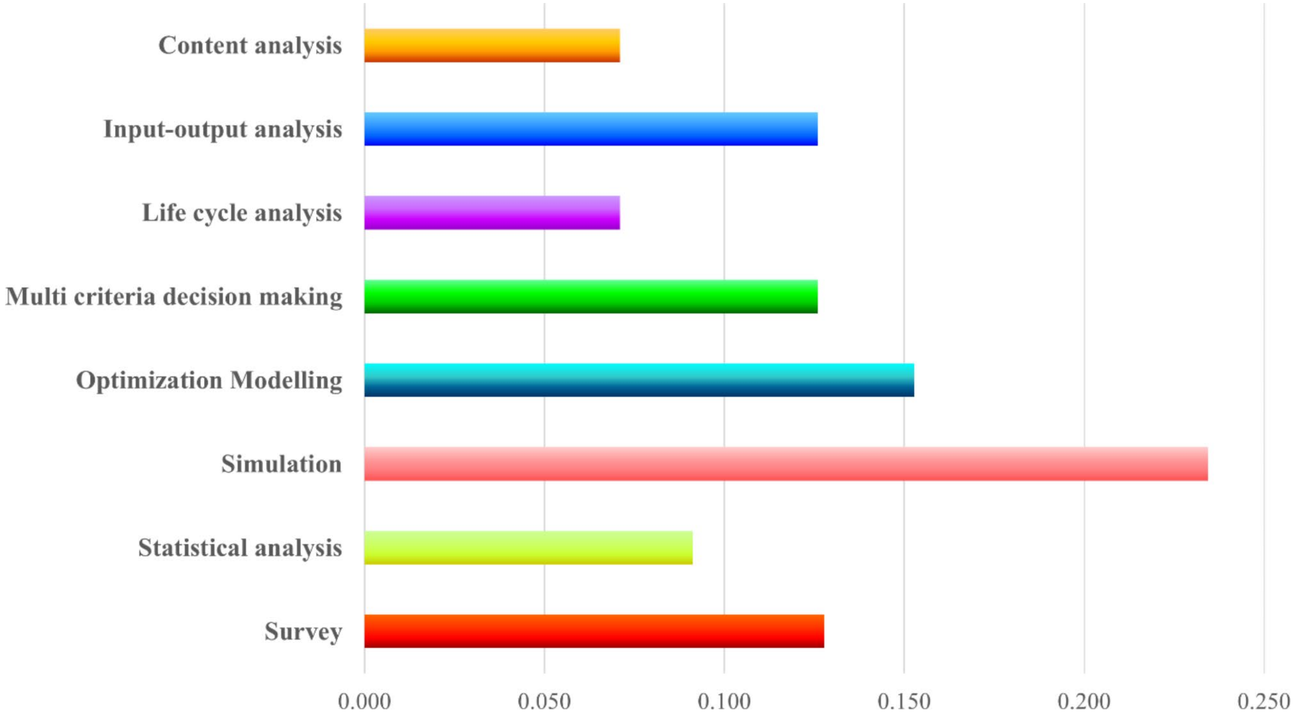

Fig. 13. Compare alternatives based on resources consumption system management.

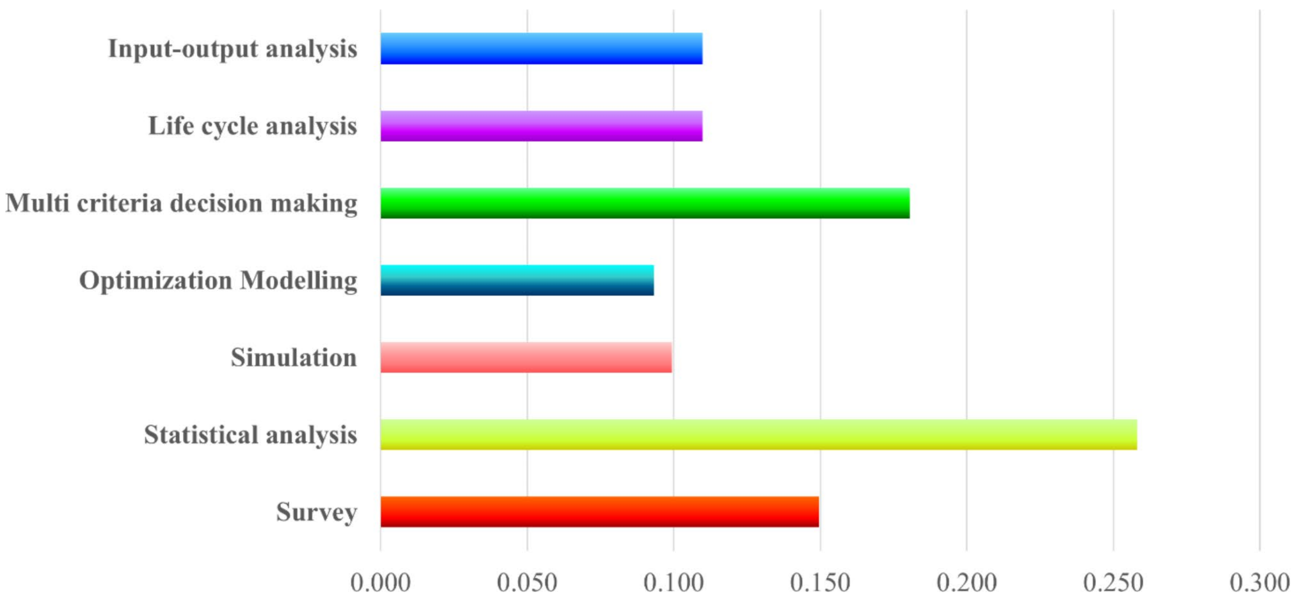

Fig. 14. Compare alternatives based on content analysis.

other methods. The findings of this mode showed that the methods of statistical analysis (normalized coefficient is equal to 0.155), simulation (normalized coefficient is equal to 0.153), survey (normalized coefficient is equal to 0.135), content analysis (normalized coefficient is equal to 0.124), input-output analysis (normalized coefficient is equal to 0.124), optimization (normalized coefficient is equal to 0.113), LCA (normalized coefficient is equal to 0.100), and MCDM (normalized coefficient is equal to 0.096) are in the hierarchy of relative importance. As the findings show, methods such as statistical analysis and survey, which were prioritized from the point of view of why, were prioritized relatively less important, due to their complementarity, they have gained significant importance in ANP analysis.

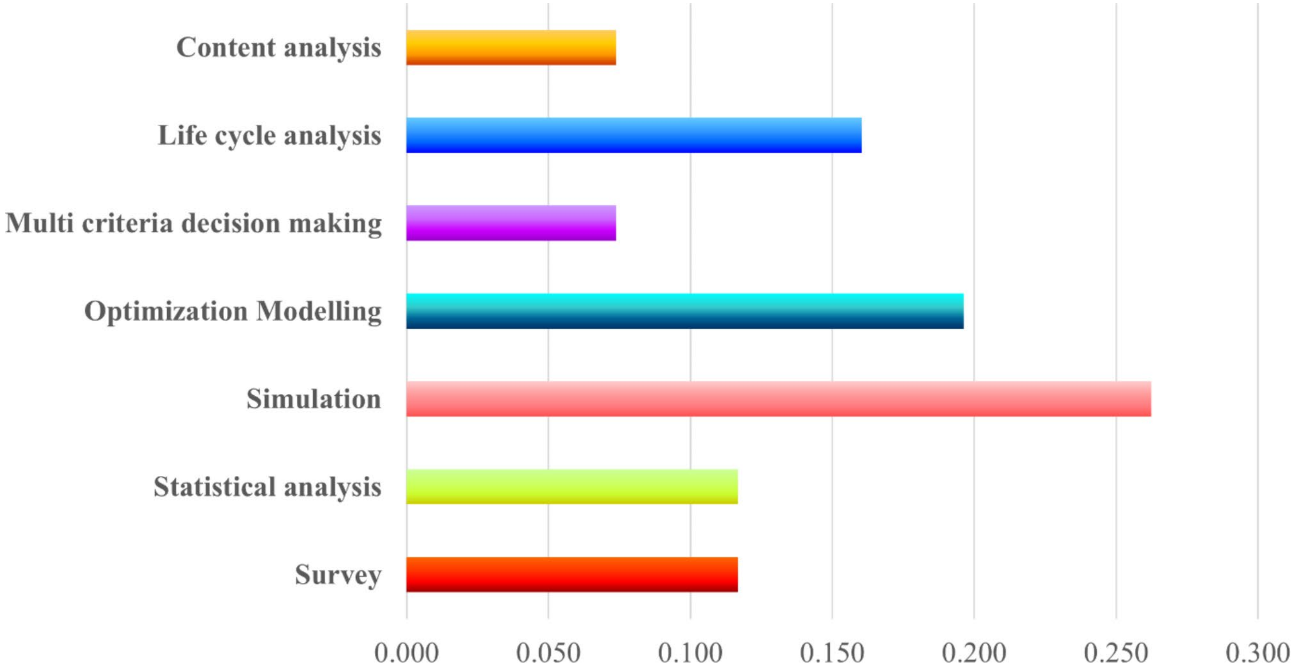

Fig. 15. Compare alternatives based on input-output analysis.

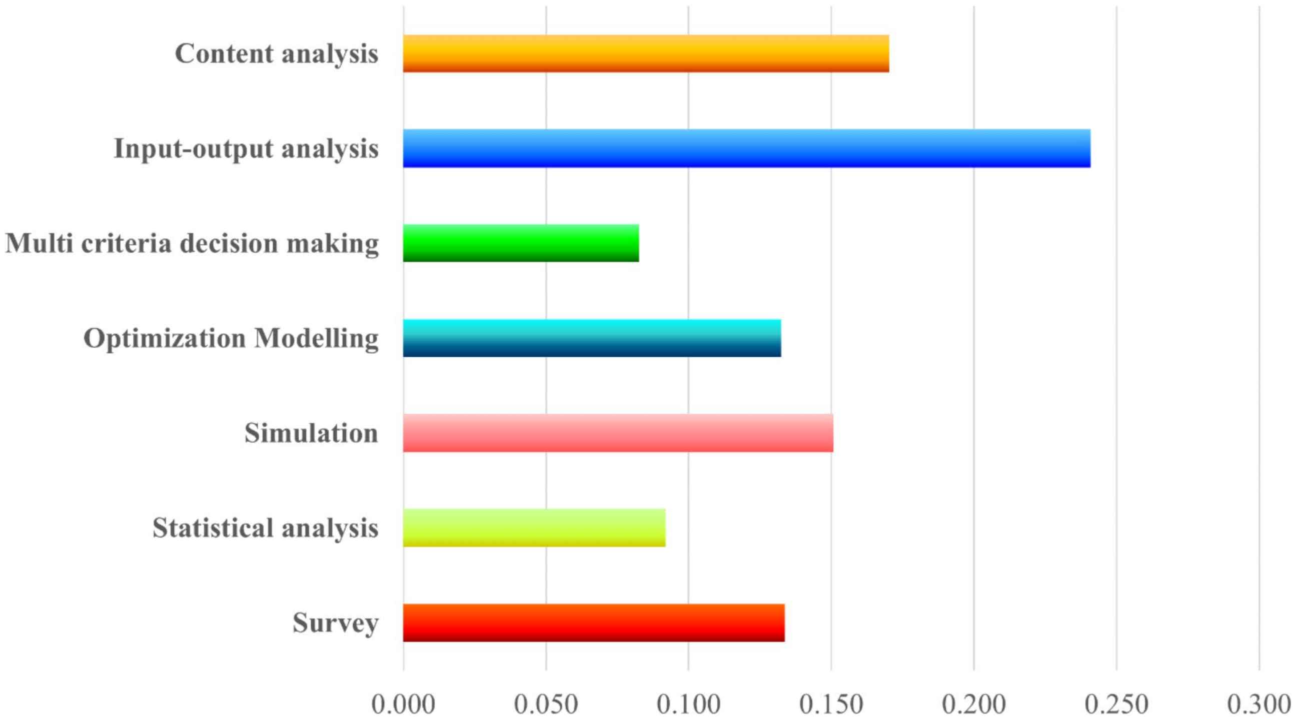

Fig. 16. Compare alternatives based on life cycle analysis (LCA).

Conclusion and recommendations

Population increases, urbanization development, economic boom, and growth, as well as the reduction of hard renewable resources, have caused countries to put a lot of pressure on available resources to achieve a better situation and maintain their current status. This double pressure on resources is being applied in the conditions of climate change. However, the failure of this pressure to achieve the goal of decreasing the problem of malnutrition in the world is obvious. The most important reason for this is the decreased quality of production resources (especially water). As a result, balancing the consumption of resources was put on the agenda of many countries

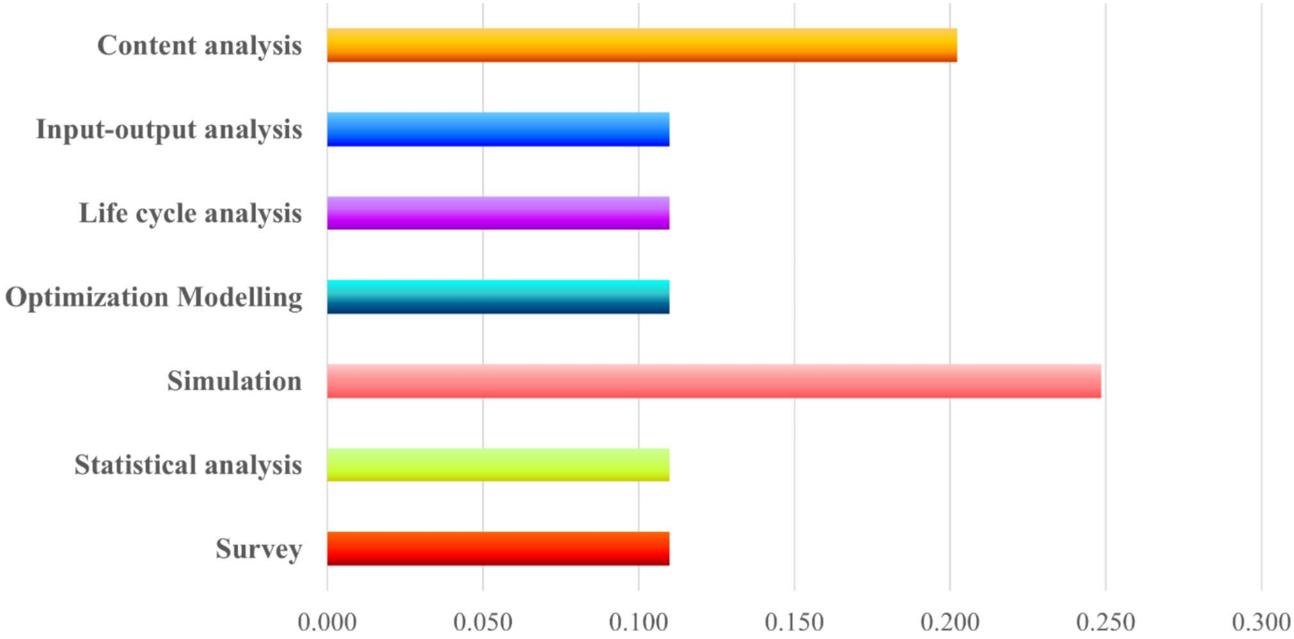

Fig. 17. Compare alternatives based on multi-criteria decision-making (MCDM).

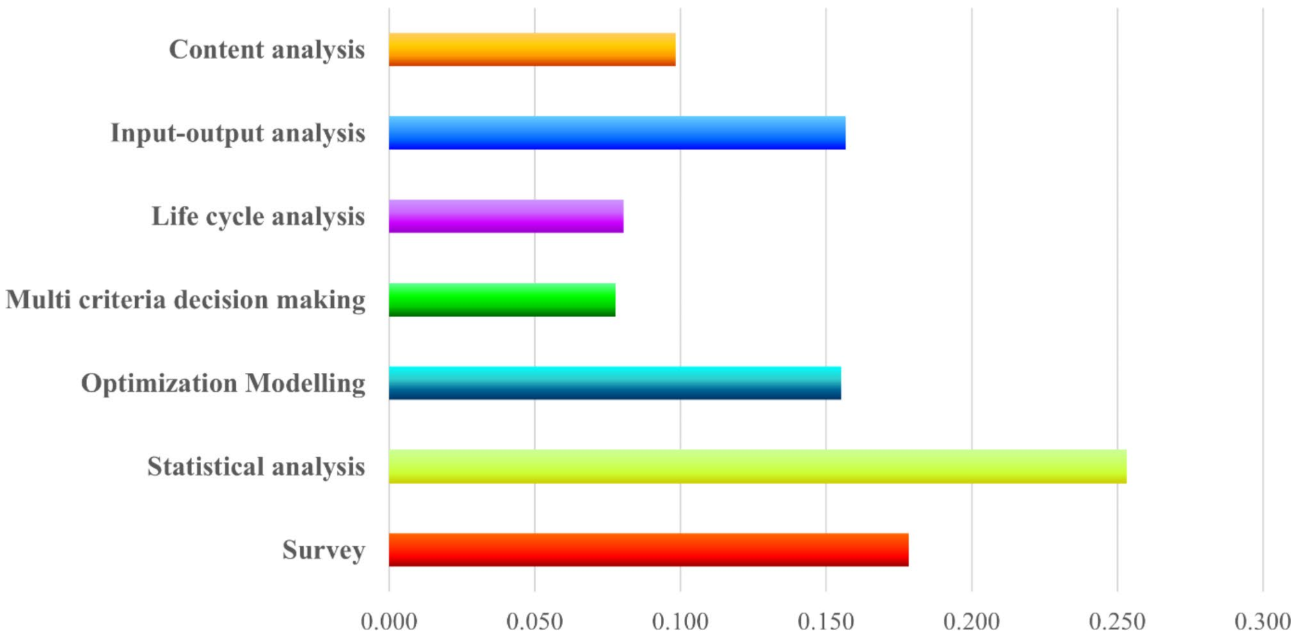

Fig. 18. Compare alternatives based on simulation.

and their experts. In response to the research need for studies on balanced and optimal resource consumption, a range of methods has been utilized. Over time, these studies have been consolidated into what are now known as nexus studies. One of the types of nexuses was WEFN, which is specific to countries and regions where energy is the most important competitor of food in the consumption of water resources. Therefore, the purpose of this study was to investigate what, why, and how to conduct WEFN studies.

The findings suggest that the objectives of WEFN studies encompass a broad spectrum of interests, which can be systematically delineated into seven principal domains: system sustainability assessment, integration of planning and decision-making processes concerning resource consumption, optimization of resource consumption, management of resource consumption systems, development of theoretical frameworks for the nexus, evaluation of the impacts of resource consumption, and assessment of associated risks.

From this category, it is evident that the majority of studies conducted focus on the sustainability of systems in light of resource consumption, aiming to yield appropriate solutions aligned with resource planning and

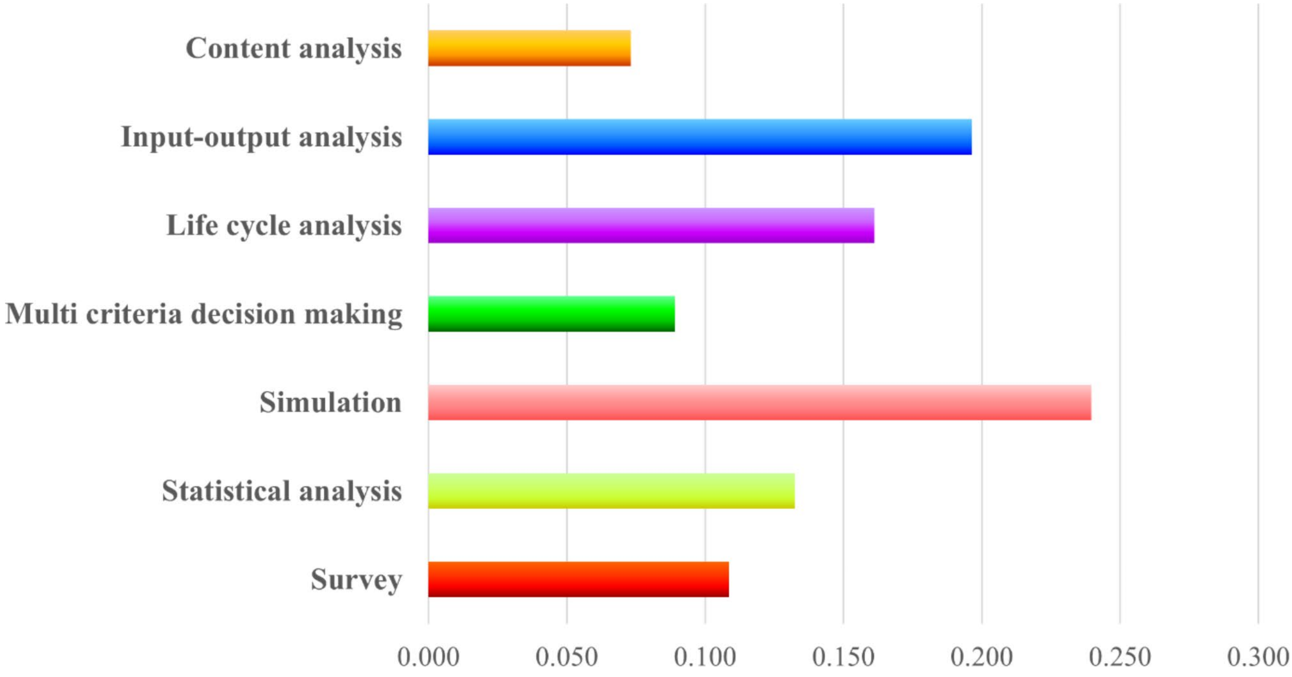

Fig. 19. Compare alternatives based on optimization modeling.

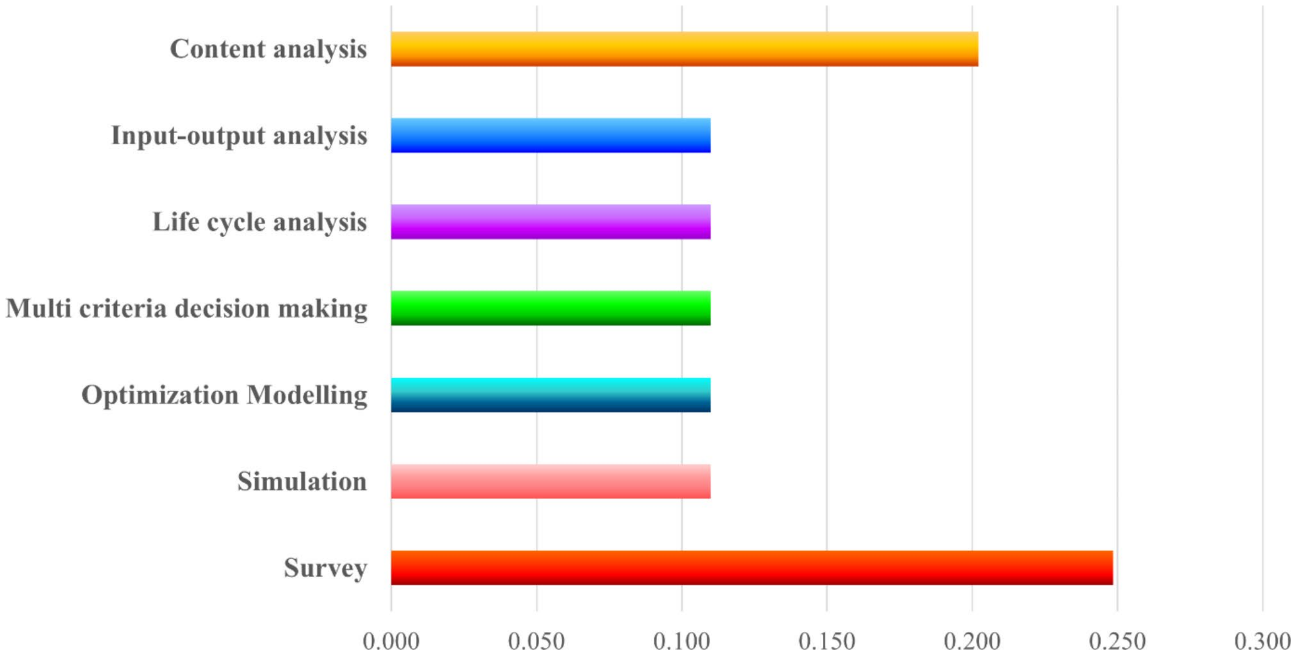

Fig. 20. Compare alternatives based on statistical analysis.

optimal management. Additionally, the research findings underscore the significance placed on evaluating system sustainability compared to other rationales for WEFN studies. However, a crucial aspect of conducting such studies is ensuring they yield decisive insights that can guide policymakers in planning and implementing effective management strategies.

Furthermore, an analysis of methods employed in conducting WEFN studies revealed that simulation, survey, content analysis, input-output analysis, Multiple Criteria Decision Making (MCDM), statistical analysis, Life Cycle Assessment (LCA), and optimization modeling were among the most commonly utilized techniques. The research also indicated that simulation emerged as the preferred method in comparative assessments based on specified criteria. Taking into account their respective criteria and their complementary nature, statistical analysis and simulation were identified as the most crucial methods. The key finding of this research underscores

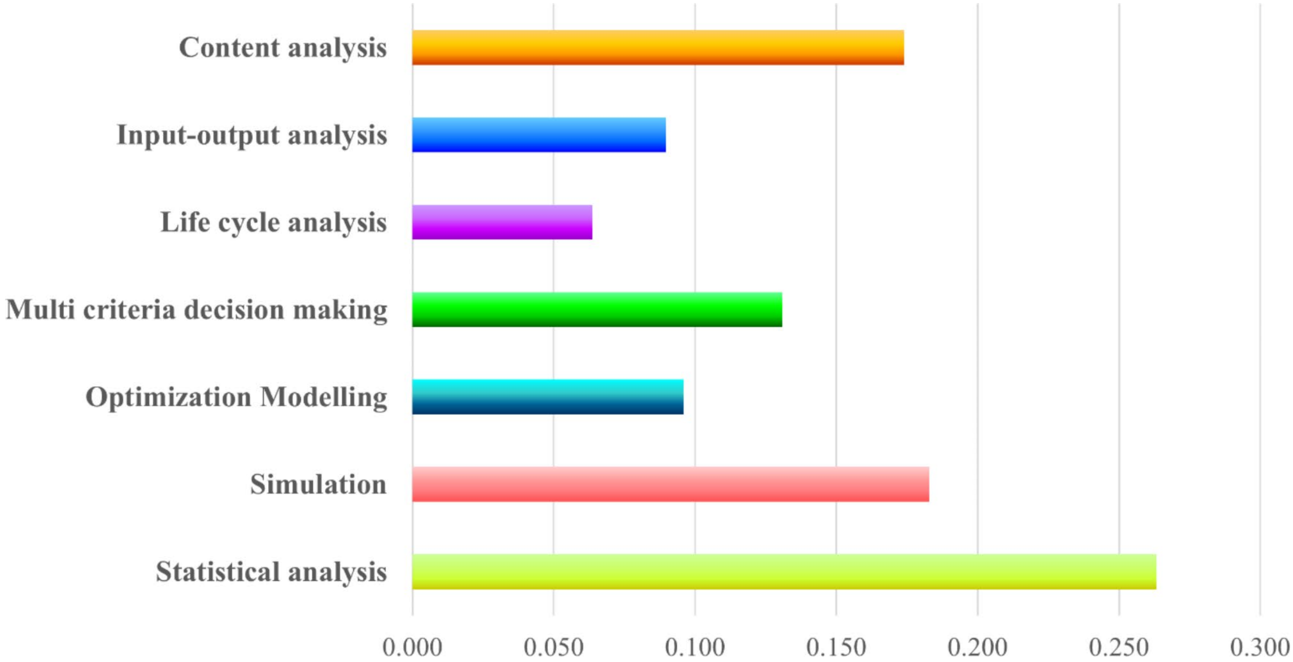

Fig. 21. Compare alternatives based on survey.

Alternatives	Content analysis	Input-output analysis	LCA	MCDM	Optimization	Simulation	Statistical analysis	Survey
Content analysis	-	0.074	0.170	0.202	0.073	0.098	0.202	0.174
Input-output analysis	0.110	-	0.241	0.110	0.197	0.157	0.110	0.090
LCA	0.110	0.160	-	0.110	0.161	0.080	0.110	0.064
MCDM	0.180	0.074	0.083	-	0.089	0.078	0.110	0.131
Optimization	0.093	0.196	0.132	0.110	-	0.155	0.110	0.096
Simulation	0.099	0.262	0.151	0.248	0.240	-	0.110	0.183
Statistical analysis	0.258	0.117	0.092	0.110	0.132	0.253	-	0.263
Survey	0.150	0.117	0.134	0.110	0.108	0.178	0.248	-
Inconsistency index	0.0139	0.0226	0.0374	0.0062	0.0431	0.0254	0.0062	0.0223

Table 5. Comparative analysis of Alternatives.

that the optimal methods for conducting WEFN studies may not always receive prioritization in comprehensive and combined research endeavors, largely due to the inherent capabilities and limitations of these methods. In multidimensional studies such as WEFN, there is a preference for methods whose outcomes can be integrated with those of other methodologies. This research proposes the use of a diagram to guide the selection of the optimal method for conducting WEFN studies (see Fig. 24). The diagram prompts consideration of six main questions that can lead them to optimal method. Two factors influencing the answers to these questions and the selection of the optimal research method are whether the research is designed for long-term or short-term findings and whether the research method is purely theoretical or applied in nature. Given the nature of WEFN studies and the demand for their results, methods that facilitate the generation of judgmental statements are recommended. Ultimately, it is suggested that studies be conducted iteratively to develop a decision support system for stakeholders within the study's scope.

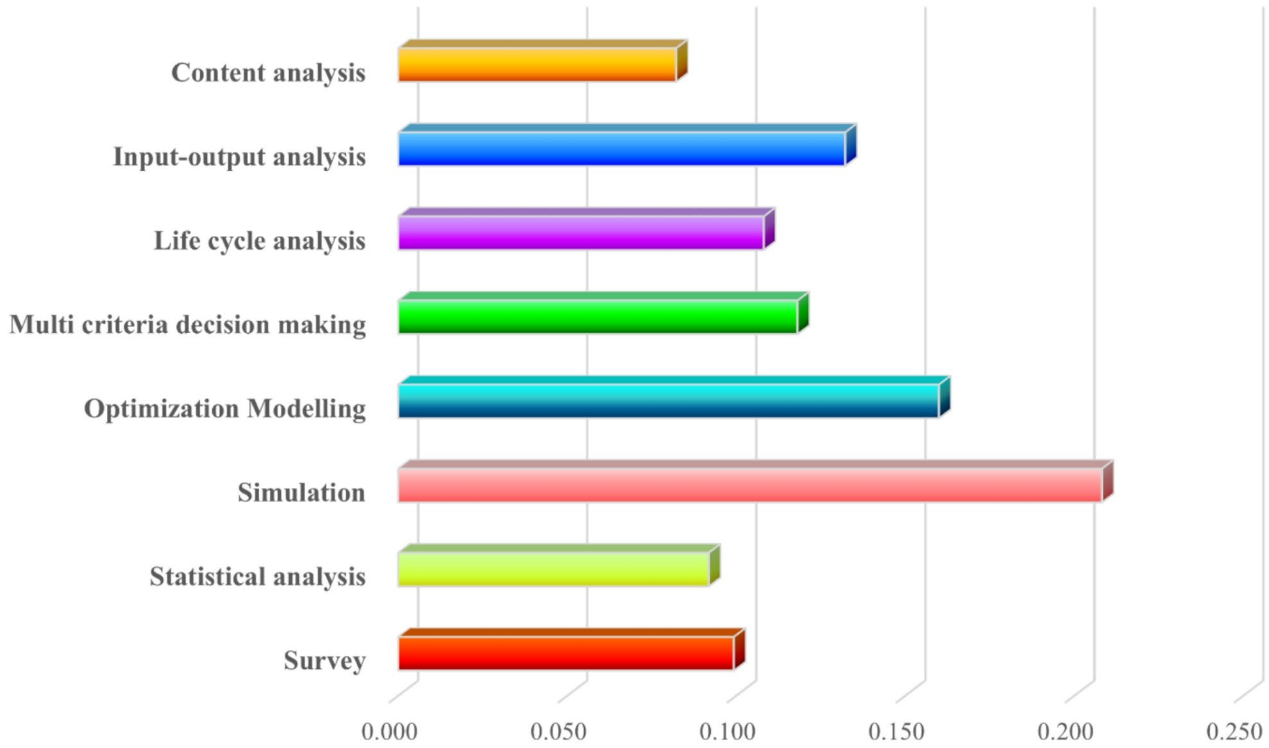

Fig. 22. Synthesized results based on AHP.

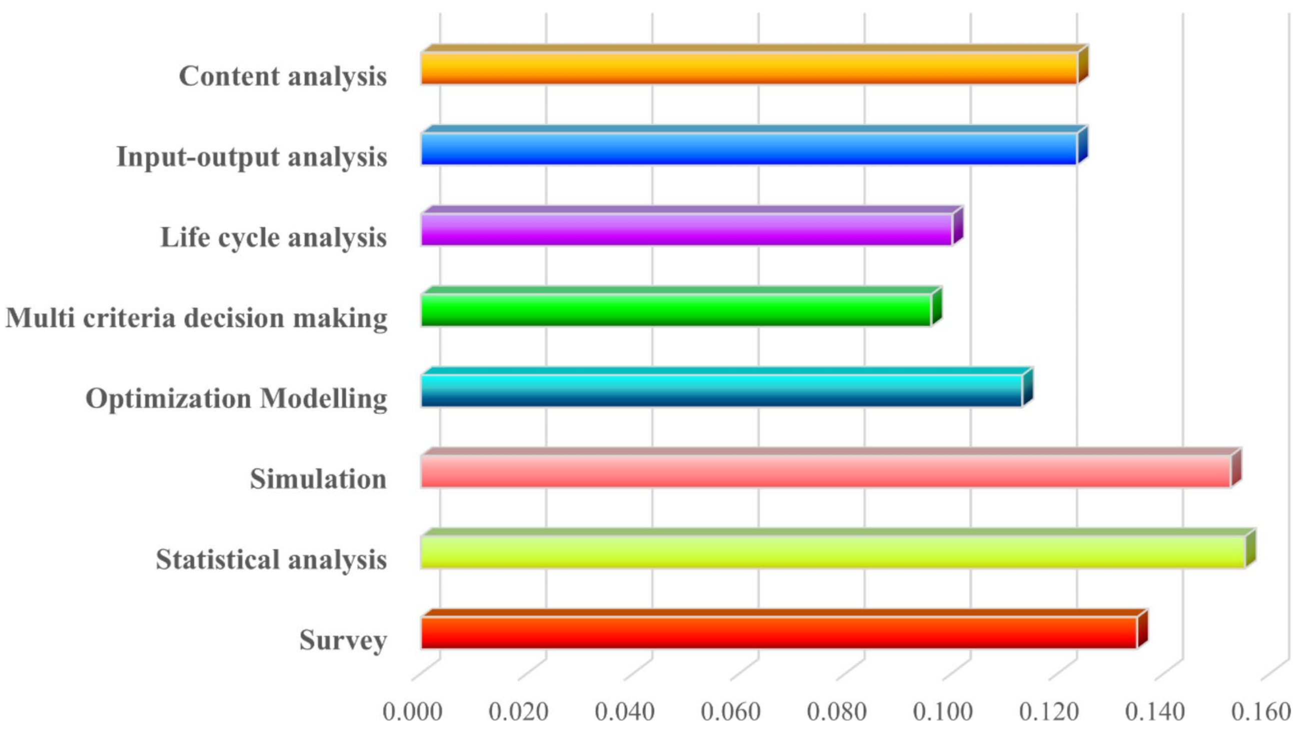

Fig. 23. Synthesized results based on ANP.

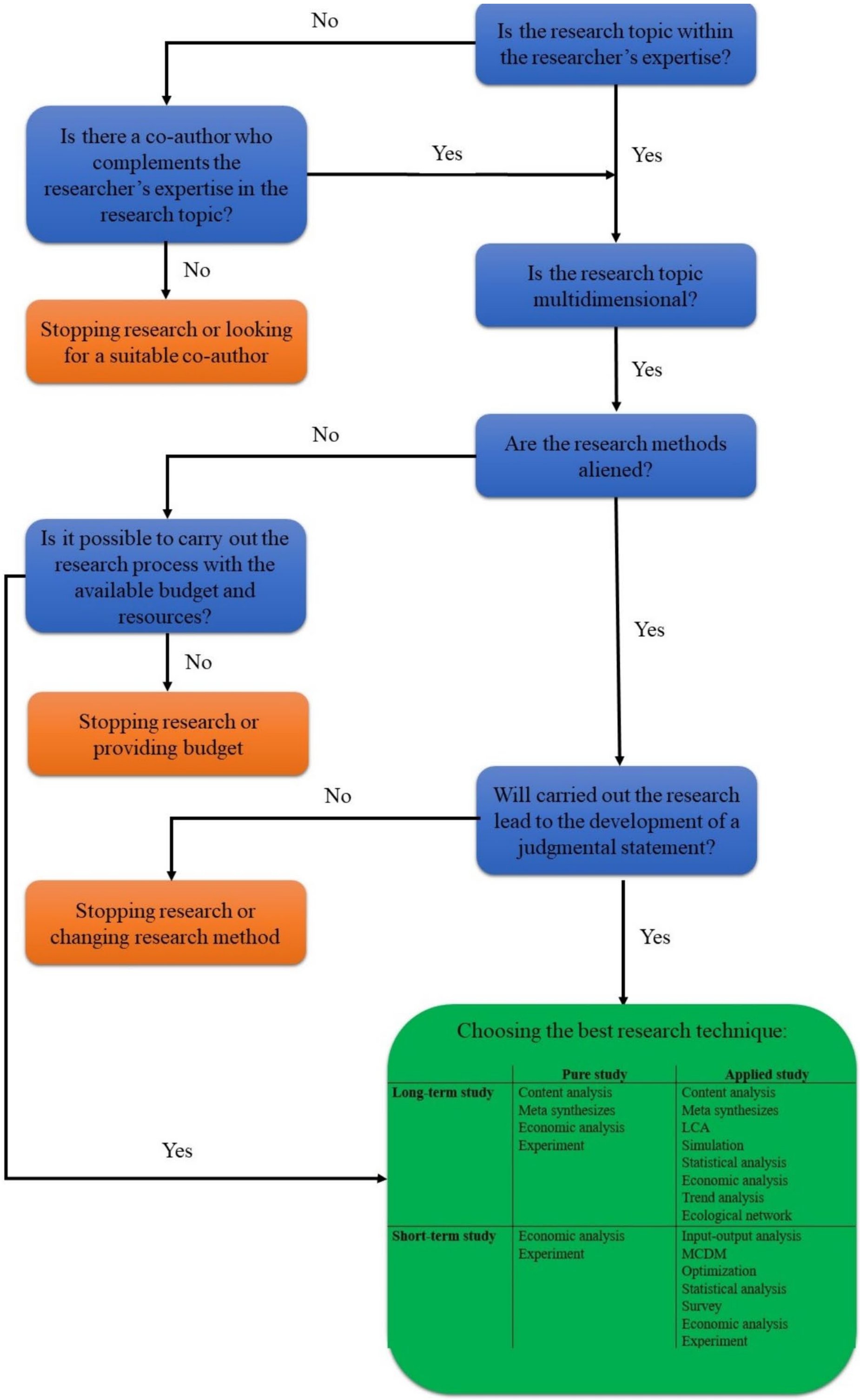

Fig. 24. the diagram for choosing the optimal method of conducting a WEFN study.

Data availability

Data will be made available by first author on request.

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References

1. Zhu, M. Water–energy–food nexus based on a new perspective of regional sustainable development. *Water Supply*. **23**, 4466–4478. https://doi.org/10.2166/ws.2023.281 (2023).
2. Wang, S. et al. Coordinated analysis and evaluation of water–energy–food coupling: A case study of the yellow river basin in Shandong province, China. *Ecol. Indic.* **148**, 110138. https://doi.org/10.1016/j.ecolind.2023.110138 (2023).
3. Biggs, E. et al. Sustainable development and the water–energy–food nexus: A perspective on livelihoods. *Environ. Sci. Policy*. **54**, 389–397. https://doi.org/10.1016/j.envsci.2015.08.002 (2015).
4. Zarei, S., Bozorg-Haddad, O., Kheirinejad, S. & Loáiciga, H. A. Environmental sustainability: A review of the water–energy–food nexus. *AQUA Water Infrastruct. Ecosyst. Soc.* **70**, 138–154. https://doi.org/10.2166/aqua.2020.058 (2021).
5. Correa-Porcel, V., Piedra-Muñoz, L. & Galdeano-Gómez, E. Water–energy–food nexus in the agri-food sector: research trends and innovating practices. *Int. J. Environ. Res. Public. Health*. **18**, 12966. https://doi.org/10.3390/ijerph182412966 (2021).
6. Hamidov, A. et al. Operationalizing water-energy-food nexus research for sustainable development in social-ecological systems: An interdisciplinary learning case in central Asia. *Ecol. Soc.* **27**, 270112. https://doi.org/10.5751/ES-12891-270112 (2022).
7. Ioannou, A. E. & Laspidou, C. S. Resilience analysis framework for a water–energy–food nexus system under climate change. *Front. Environ. Sci.* **10**, 820125. https://doi.org/10.3389/fenvs.2022.820125 (2022).
8. Kellner, E. Identifying leverage points for shifting water-energy-food nexus cases towards sustainability through the networks of action situations approach combined with systems thinking. *Sustain. Sci.* **18**, 135–152. https://doi.org/10.1007/s11625-022-01170-7 (2023).
9. Liu, S. et al. Evaluation of water-energy-food-ecology system development in Beijing-Tianjin-Hebei Region from a symbiotic perspective and analysis of influencing factors. *Sustainability*. **15**, 5138. https://doi.org/10.3390/su15065138 (2023).
10. Lucca, E. et al. A review of water-energy-food-ecosystems nexus research in the Mediterranean: evolution, gaps and applications. *Environ. Res. Lett.* **18** (2023).
11. D'Odorico, P. et al. The global food-energy-water nexus. *Rev. Geo.* **56**, 456–531. https://doi.org/10.1029/2017RG000591 (2018).
12. Fernández-Ríos, A. et al. Towards a water-energy-food (wef) nexus index: a review of nutrient profile models as a fundamental pillar of food and nutrition security. *Sci. Total Environ.* **789**, 147936. https://doi.org/10.1016/j.scitotenv.2021.147936 (2021).
13. GlobalHungerIndex. *Global Hunger Index 2023: The power of youth in shaping food systems*. (2023). https://globalhungerindex.org
14. USDA. *Data products from USDA Economic Research Service* (2019). http://www.ers.usda.gov
15. Steffen, A. D. *The countries most at risk from climate change* (2020). https://www.intelligentliving.co/maps-countries-survive-climate-change
16. Mpandeli, S. et al. Climate change adaptation through the water-energy-food nexus in southern Africa. *Int. J. Environ. Res. Public. Health*. **15**, 2306. https://doi.org/10.3390/ijerph15102306 (2018).
17. Wakdok, S. S. & Bleischwitz, R. Climate change, security, and the resource nexus: case study of northern Nigeria and lake Chad. *Sustainability*. **13**, 10734. https://doi.org/10.3390/su131910734 (2021).
18. Salmoral, G., Schaap, N. C., Walschebauer, J. & Alhajaj, A. Water diplomacy and nexus governance in a transboundary context: In the search for complementarities. *Sci. Total Environ.* **690**, 85–96. https://doi.org/10.1016/j.scitotenv.2019.06.513 (2019).
19. Urbinatti, A. M., Fontana, D., Stirling, M., Giatti, L. L. & A. & Opening up'the governance of water-energy-food nexus: towards a science-policy-society interface based on hybridity and humility. *Sci. Total Environ.* **744**, 140945. https://doi.org/10.1016/j.scitotenv.2020.140945 (2020).
20. Zhang, C., Chen, X., Li, Y., Ding, W. & Fu, G. Water-energy-food nexus: concepts, questions and methodologies. *J. Clean. Prod.* **195**, 625–639. https://doi.org/10.1016/j.jclepro.2018.05.194 (2018).
21. Liu, J. et al. Challenges in operationalizing the water–energy–food nexus. *Hydrol. Sci. J.* **62**, 1714–1720. https://doi.org/10.1080/02626667.2017.1353695 (2017).
22. Saaty, T. L. of referencing in *Theory and applications of the analytic network process: Decision making with benefits, opportunities, costs, and risks*RWS publications, (2005).
23. Sharifi Moghadam, E., Sadeghi, S., Zarghami, M. & Delavar, M. Water-energy-food nexus as a new approach for watershed resources management: A review. *Environ. Resour. Res.* **7**, 129–135. https://doi.org/10.22069/ijerr.2019.4820 (2019).
24. Endo, A. et al. Dynamics of water–energy–food nexus methodology, methods, and tools. *Curr. Opin. Environ. Sci. Health.* **13**, 46–60. https://doi.org/10.1016/j.coesh.2019.10.004 (2020).
25. Radmehr, R., Ghorbani, M. & Ziaei, A. N. Quantifying and managing the water-energy-food nexus in dry regions food insecurity: New methods and evidence. *Agric. Water Manage.* **245**, 106588. https://doi.org/10.1016/j.agwat.2020.106588 (2021).
26. Abulibdeh, A. & Zaidan, E. Managing the water-energy-food nexus on an integrated geographical scale. *Environ. Dev.* **33**, 100498. https://doi.org/10.1016/j.envdev.2020.100498 (2020).
27. Bakhshianlamouki, E., Masia, S., Karimi, P., van der Zaag, P. & Sušnik, J. A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake basin, Iran. *Sci. Total Environ.* **708**, 134874. https://doi.org/10.1016/j.scitotenv.2019.134874 (2020).
28. Boluwade, A. Impacts of climatic change and database information design on the water-energy-food nexus in water-scarce regions. *Water Energy Nexus*. **4**, 54–68. https://doi.org/10.1016/j.wen.2021.03.002 (2021).
29. Chen, C. F., Feng, K. L. & Ma, H. W. Uncover the interdependent environmental impacts associated with the water-energy-food nexus under resource management strategies. *Resour. Conserv. Recycl.* **160**, 10409. https://doi.org/10.1016/j.resconrec.2020.104909 (2020).
30. Sharifinejad, A., Zahraie, B., Majed, V., Ravar, Z. & Hassani, Y. Economic analysis of water-food-energy nexus in Gavkhuni basin in Iran. *J. Hydro-environ Res.* **31**, 14–25. https://doi.org/10.1016/j.jher.2020.03.001 (2020).
31. Wang, X. C. et al. Extended water-energy nexus contribution to environmentally-related sustainable development goals. *Renew. Sustainable Energy Rev.* **150**, 111485. https://doi.org/10.1016/j.rser.2021.111485 (2021a).
32. Yu, L. et al. A copula-based fuzzy interval-random programming approach for planning water-energy nexus system under uncertainty. *Energy*. **196**, 117063. https://doi.org/10.1016/j.energy.2020.117063 (2020).
33. Yue, Q. & Guo, P. Managing agricultural water-energy-food-environment nexus considering water footprint and carbon footprint under uncertainty. *Agric. Water Manage.* **252**, 106899. https://doi.org/10.1016/j.agwat.2021.106899 (2021).
34. Abdel-Aal, M., Haltas, I. & Varga, L. Modeling the diffusion and operation of anaerobic digestions in Great Britain under future scenarios within the scope of water-energy-food nexus. *J. Clean. Prod.* **253**, 119897. https://doi.org/10.1016/j.jclepro.2019.119897 (2020).
35. Anser, M. K. et al. Management of water, energy, and food resources: Go for green policies. *J. Clean. Prod.* **251**, 119662. https://doi.org/10.1016/j.jclepro.2019.119662 (2020).
36. Chai, J., Shi, H., Lu, Q. & Hu, Y. Quantifying and predicting the water-energy-food-economy-society-environment nexus based on bayesian networks: A case study of China. *J. Clean. Prod.* **256**, 120266. https://doi.org/10.1016/j.jclepro.2020.120266 (2020).
37. Cheng, Y., Wang, J. & Shu, K. The coupling and coordination assessment of food-water-energy systems in China based on sustainable development goals. *Sustainable Prod. Consum.* **35**, 338–348. https://doi.org/10.1016/j.spc.2022.11.011 (2023).
38. Correa-Cano, M. et al. A novel modelling toolkit for unpacking the water-energy-food-environment (wefe) nexus of agricultural development. *Renew. Sustainable Energy Rev.* **159**, 112182. https://doi.org/10.1016/j.rser.2022.112182 (2022).
39. Fabiani, S., Vanino, S., Napoli, R. & Nino, P. Water energy food nexus approach for sustainability assessment at farm level: An experience from an intensive agricultural area in central Italy. *Environ. Sci. Policy*. **104**, 1–12. https://doi.org/10.1016/j.envsci.2019.10.008 (2020).

40. Lawford, R. et al. Basin perspectives on the water–energy–food security nexus. *Curr. Opin. Environ. Sustain.* **5**, 607–616. https://doi.org/10.1016/j.cosust.2013.11.005 (2013).
41. Mannan, M., Al-Ansari, T., Mackey, H. R. & Al-Ghamdi, S. G. Quantifying the energy, water and food nexus: A review of the latest developments based on life-cycle assessment. *J. Clean. Prod.* **193**, 300–314. https://doi.org/10.1016/j.jclepro.2018.05.050 (2018).
42. Naghavi, S., Mirzaei, A., Sardoei, M. A. & Azarm, H. Evaluating the synergy between water-energy-food nexus and decoupling pollution-agricultural growth for sustainable production in the agricultural sector. *Res. Square*. **10**, 21203. https://doi.org/10.21203/rs.3.rs-2024368/v1 (2022).
43. Ngarava, S. Long term relationship between food, energy and water inflation in South Africa. *Water-Energy Nexus*. **4**, 123–133. https://doi.org/10.1016/j.wen.2021.07.002 (2021).
44. Nhamo, L. & Ndlela, B. Nexus planning as a pathway towards sustainable environmental and human health post covid-19. *Environ. Res.* **192**, 110376. https://doi.org/10.1016/j.envres.2020.110376 (2021).
45. Niu, S., Lyu, X. & Gu, G. A new framework of green transition of cultivated land-use for the coordination among the water-land-food-carbon nexus in China. *Land*. **11**, 933. https://doi.org/10.3390/land11060933 (2022).
46. Qian, X. Y. & Liang, Q. M. Sustainability evaluation of the provincial water-energy-food nexus in China: Evolutions, obstacles, and response strategies. *Sustainable Cities Soc.* **75**, 103332. https://doi.org/10.1016/j.scs.2021.103332 (2021).
47. Saladini, F. et al. Linking the water-energy-food nexus and sustainable development indicators for the Mediterranean region. *Ecol. Indic.* **91**, 689–697. https://doi.org/10.1016/j.ecolind.2018.04.035 (2018).
48. Wang, Q., Li, S., He, G., Li, R. & Wang, X. Evaluating sustainability of water-energy-food (wef) nexus using an improved matter-element extension model: A case study of China. *J. Clean. Prod.* **202**, 1097–1106. https://doi.org/10.1016/j.jclepro.2018.08.213 (2018).
49. Wu, L., Elshorbagy, A., Pande, S. & Zhuo, L. Trade-offs and synergies in the water-energy-food nexus: The case of Saskatchewan, Canada. *Resour. Conserv. Recycl.* **164**, 105192. https://doi.org/10.1016/j.resconrec.2020.105192 (2021).
50. Xu, S. et al. Coupling and coordination degrees of the core water–energy–food nexus in China. *Int. J. Environ. Res. Public. Health*. **16**, 1648. https://doi.org/10.3390/ijerph16091648 (2019).
51. Yi, J. et al. Sustainability assessment of the water-energy-food nexus in Jiangsu province, China. *Habitat Int.* **95**, 102094. https://doi.org/10.1016/j.habitatint.2019.102094 (2020).
52. Zhang, P. et al. Water-energy-food system in typical cities of the world and China under zero-waste: commonalities and asynchronous experiences support sustainable development. *Ecol. Indic.* **132**, 108221. https://doi.org/10.1016/j.ecolind.2021.108221 (2021b).
53. Zhang, P. et al. Assessment of the water-energy-food nexus under spatial and social complexities: A case study of Guangdong-HongKong-Macao. *J. Environ. Manage.* **299**, 113664. https://doi.org/10.1016/j.jenvman.2021.113664 (2021c).
54. Akinsete, E. et al. Sustainable wef nexus management: a conceptual framework to integrate models of social, economic, policy, and institutional developments. *Front. Water*. **4**, 727772. https://doi.org/10.3389/frwa.2022.727772 (2022).
55. Bazzana, D., Gilioli, G., Simane, B. & Zaitchik, B. Analyzing constraints in the water-energy-food nexus: The case of eucalyptus plantation in Ethiopia. *Ecol. Econ.* **180**, 106875. https://doi.org/10.1016/j.ecolecon.2020.106875 (2021).
56. Caputo, S. et al. Applying the food-energy-water nexus approach to urban agriculture: From few to fewp (food-energy-water-people). *Urban Urban Green.* **58**, 126934. https://doi.org/10.1016/j.ufug.2020.126934 (2021).
57. Daher, B. et al. Towards bridging the water gap in Texas: A water-energy-food nexus approach. *Sci. Total Environ.* **647**, 449–463. https://doi.org/10.1016/j.scitotenv.2018.07.398 (2019).
58. Huang, D., Li, G., Sun, C. & Liu, Q. Exploring interactions in the local water-energy-food nexus (wef-nexus) using a simultaneous equations model. *Sci. Total Environ.* **703**, 135034. https://doi.org/10.1016/j.scitotenv.2019.135034 (2020).
59. Kedir, Y., Berhanu, B. & Alamirew, T. Analysis of water–energy–crop nexus indicators in irrigated sugarcane of Awash basin, Ethiopia. *Environ. Syst. Res.* **11**, 1–19. https://doi.org/10.1186/s40068-022-00263-7 (2022).
60. Ledari, M. B., Saboohi, Y. & Azamian, S. Water-food-energy-ecosystem nexus model development: Resource scarcity and regional development. *Energy Nexus*. **10**, 100207. https://doi.org/10.1016/j.nexus.2023.100207 (2023).
61. Li, J. et al. Valuing the synergy in the water-energy-food nexus for cropping systems: A case in the north China plain. *Ecol. Indic.* **127**, 107741 (2021).
62. Sadeghi, S. H., Moghadam, E. S., Delavar, M. & Zarghami, M. Application of water-energy-food nexus approach for designating optimal agricultural management pattern at a watershed scale. *Agric. Water Manage.* **233**, 106071. https://doi.org/10.1016/j.agwat.2020.106071 (2020).
63. Shahbaz, P. et al. Food, energy, and water nexus at household level: Do sustainable household consumption practices promote cleaner environment? *Int. J. Environ. Res. Public. Health*. **19**, 12945. https://doi.org/10.3390/ijerph191912945 (2022).
64. Tan, A. H. P., Yap, E. H. & Abakr, Y. A. A complex systems analysis of the water-energy nexus in Malaysia. *Systems*. **8**, 8020019. https://doi.org/10.3390/systems8020019 (2020).
65. Wa'el, A., Memon, H., Savic, D. A. & F. A. & An integrated model to evaluate water-energy-food nexus at a household scale. *Environ. l Model. Softw.* **93**, 366–380. https://doi.org/10.1016/j.envsoft.2017.03.034 (2017).
66. Zhang, X. & Vesselinov, V. V. Integrated modeling approach for optimal management of water, energy and food security nexus. *Adv. Water Resour.* **101**, 1–10. https://doi.org/10.1016/j.advwatres.2016.12.017 (2017).
67. Almulla, Y., Ramirez, C., Joyce, B., Huber-Lee, A. & Fuso-Nerini, F. From participatory process to robust decision-making: an agriculture-water-energy nexus analysis for the Souss-Massa basin in Morocco. *Energy Sustainable Dev.* **70**, 314–338. https://doi.org/10.1016/j.esd.2022.08.009 (2022).
68. Alzaabi, M. S. A. & Mezher, T. Analyzing existing UAE national water, energy and food nexus related strategies. *Renew. Sustainable Energy Rev.* **144**, 111031. https://doi.org/10.1016/j.rser.2021.111031 (2021).
69. Daher, B. T. & Mohtar, R. H. of referencing in *Water–energy–food (wef) nexus tool 2.0: guiding integrative resource planning and decision-making* (ed. Bhaduri, A., Ringler. C., Dombrowsky, I., Mohtar, R. H & Scheumann, W.) 748–771; 10.4324/9781315408828 (Routledge, 2015).
70. Enayati, M., Bozorg-Haddad, O., Fallah-Mehdipour, E., Zolghadr-Asli, B. & Chu, X. A robust multiple-objective decision-making paradigm based on the water–energy–food security nexus under changing climate uncertainties. *Sci. Rep.* **11**, 20927. https://doi.org/10.1038/s41598-021-99637-7 (2021).
71. Ghodsvali, M., Dane, G. & de Vries, B. The nexus social-ecological system framework (NexSESF): A conceptual and empirical examination of transdisciplinary food-water-energy nexus. *Environ. Sci. Policy*. **130**, 16–24. https://doi.org/10.1016/j.envsci.2022.01.010 (2022).
72. Hoff, H. et al. A nexus approach for the MENA region: From concept to knowledge to action. *Front. Environ. Sci.* **7**, 48. https://doi.org/10.3389/fenvs.2019.00048 (2019).
73. Li, G., Huang, D., Sun, C. & Li, Y. Developing interpretive structural modeling based on factor analysis for the water-energy-food nexus conundrum. *Sci. Total Environ.* **651**, 309–322. https://doi.org/10.1016/j.scitotenv.2018.09.188 (2019a).
74. Li, G., Wang, Y. & Li, Y. Synergies within the water-energy-food nexus to support the integrated urban resources governance. *Water*. **11**, 2365. https://doi.org/10.3390/w11112365 (2019b).
75. Mirzaei, A., Ashktorab, N. & Noshad, M. Evaluation of the policy options to adopt a water-energy-food nexus pattern by farmers: application of optimization and agent-based models. *Front. Environ. Sci.* **11**, 1139565. https://doi.org/10.3389/fenvs.2023.1139565 (2023).

76. Momblanch, A. et al. Untangling the water-food-energy-environment nexus for global change adaptation in a complex himalayan water resource system. *Sci. Total Environ.* **655**, 35–47. https://doi.org/10.1016/j.scitotenv.2018.11.045 (2019).
77. Norouzi, N. & Kalantari, G. The food-water-energy nexus governance model: A case study for Iran. *Water-Energy Nexus*. **3**, 72–80 (2020).
78. Purwanto, A., Sušnik, J., Suryadi, F. & de Fraiture, C. Quantitative simulation of the water-energy-food (wef) security nexus in a local planning context in Indonesia. *Sustainable Prod. Consum.* **25**, 198–216. https://doi.org/10.1016/j.spc.2020.08.009 (2021).
79. Rahmani, M., Jahromi, S. H. M. & Darvishi, H. H. SD-DSS model of sustainable groundwater resources management using the water-food-energy security Nexus in Alborz Province. *Ain Shams Eng. J.* **14**, 101812. https://doi.org/10.1016/j.asej.2022.101812 (2023).
80. Rising, J. Decision-making and integrated assessment models of the water-energy-food nexus. *Water Secur.* **9**, 100056. https://doi.org/10.1016/j.wasec.2019.100056 (2020).
81. Simpson, G. B. et al. The water-energy-food nexus index: A tool to support integrated resource planning, management and security. *Front. Water*. **4**, 825854. https://doi.org/10.3389/frwa.2022.825854 (2022).
82. Teitelbaum, Y., Yakirevich, A., Gross, A. & Sorek, S. Simulations of the water food energy nexus for policy driven intervention. *Heliyon*. **6**, e04767. https://doi.org/10.1016/j.heliyon.2020.e04767 (2020).
83. Wu, N., Xu, Y., Liu, X., Wang, H. & Herrera-Viedma, E. Water–energy–food nexus evaluation with a social network group decision making approach based on hesitant fuzzy preference relations. *Appl. Soft Comput.* **93**, 106363. https://doi.org/10.1016/j.asoc.2020.106363 (2020).
84. Ali, M., Anjum, M. N., Shangguan, D. & Hussain, S. Water, energy, and food nexus in Pakistan: parametric and non-parametric analysis. *Sustainability*. **14**, 13784. https://doi.org/10.3390/su142113784 (2022).
85. El-Gafy, I. Water–food–energy nexus index: analysis of water–energy–food nexus of crop's production system applying the indicators approach. *Appl. Water Sci.* **7**, 2857–2868. https://doi.org/10.1007/s13201-017-0551-3 (2017).
86. Golfam, P., Ashofteh, P. S. & Loáiciga, H. A. Modeling adaptation policies to increase the synergies of the water-climate-agriculture nexus under climate change. *Environ. Dev.* **37**, 100612. https://doi.org/10.1016/j.envdev.2021.100612 (2021).
87. Haltas, I., Suckling, J., Soutar, I., Druckman, A. & Varga, L. Anaerobic digestion: A prime solution for water, energy and food nexus challenges. *Energy Procedia*. **123**, 22–29. https://doi.org/10.1016/j.egypro.2017.07.280 (2017).
88. Ibrahim, M. D., Ferreira, D. C., Daneshvar, S. & Marques, R. C. Transnational resource generativity: Efficiency analysis and target setting of water, energy, land, and food nexus for OECD countries. *Sci. Total Environ.* **697**, 134017. https://doi.org/10.1016/j.scitotenv.2019.134017 (2019).
89. Khattar, R. et al. Incorporating nitrogen in the water-energy-food nexus: An optimization approach. *Clean. Circ. Bioecon.* **4**, 100036. https://doi.org/10.1016/j.clcb.2023.100036 (2023).
90. Lazaro, L. L. B., Giatti, L. L., Bermann, C., Giarolla, A. & Ometto, J. Policy and governance dynamics in the water-energy-food-land nexus of biofuels: Proposing a qualitative analysis model. *Renew. Sustainable Energy Rev.* **149**, 111384. https://doi.org/10.1016/j.rser.2021.111384 (2021a).
91. Lehmann, S. Implementing the urban nexus approach for improved resource-efficiency of developing cities in southeast Asia. *City Cult. Soc.* **13**, 46–56. https://doi.org/10.1016/j.ccs.2017.10.003 (2018).
92. Mahlknecht, J., González-Bravo, R. & Loge, F. J. Water-energy-food security: A nexus perspective of the current situation in Latin America and the Caribbean. *Energy*. **194**, 116824. https://doi.org/10.1016/j.energy.2019.116824 (2020).
93. Namany, S., Al-Ansari, T. & Govindan, R. Optimisation of the energy, water, and food nexus for food security scenarios. *Computers Chem. Engin*. **129**, 106513. https://doi.org/10.1016/j.compchemeng.2019.106513 (2019).
94. Nie, Y. et al. A food-energy-water nexus approach for land use optimization. *Sci. Total Environ.* **659**, 7–19. https://doi.org/10.1016/j.scitotenv.2018.12.242 (2019).
95. Shen, Q., Niu, J., Liu, Q., Liao, D. & Du, T. A resilience-based approach for water resources management over a typical agricultural region in northwest China under water-energy-food nexus. *Ecol. Indic.* **144**, 109562. https://doi.org/10.1016/j.ecolind.2022.109562 (2022).
96. Terrapon-Pfaff, J., Ortiz, W., Dienst, C. & Gröne, M. C. Energising the wef nexus to enhance sustainable development at local level. *J. Environ. Manage.* **223**, 409–416. https://doi.org/10.1016/j.jenvman.2018.06.037 (2018).
97. Uen, T. S., Chang, F. J., Zhou, Y. & Tsai, W. P. Exploring synergistic benefits of water-food-energy nexus through multi-objective reservoir optimization schemes. *Sci. Total Environ.* **633**, 341–351. https://doi.org/10.1016/j.scitotenv.2018.03.172 (2018).
98. Zeng, Y. et al. Assessing the effects of water resources allocation on the uncertainty propagation in the water–energy–food–society (wefs) nexus. *Agric. Water Manage.* **282**, 108279. https://doi.org/10.1016/j.agwat.2023.108279 (2023).
99. Zuo, Q., Wu, Q., Yu, L., Li, Y. & Fan, Y. Optimization of uncertain agricultural management considering the framework of water, energy and food. *Agric. Water Manage.* **253**, 106907. https://doi.org/10.1016/j.agwat.2021.106907 (2021).
100. Babel, M. S., Rahman, M., Budhathoki, A. & Chapagain, K. Optimization of economic return from water using water-energy-food nexus approach: A case of Karnafuli basin, Bangladesh. *Energy Nexus*. **10**, 100186. https://doi.org/10.1016/j.nexus.2023.100186 (2023).
101. Bazzana, D., Zaitchik, B. & Gilioli, G. Impact of water and energy infrastructure on local well-being: An agent-based analysis of the water-energy-food nexus. *Struc Change Econ. Dyn.* **55**, 165–176. https://doi.org/10.1016/j.strueco.2020.08.003 (2020).
102. Ghimire, U., Piman, T., Shrestha, M., Aryal, A. & Krittasudthacheewa, C. Assessment of climate change impacts on the water, food, and energy sectors in sittaung river basin, Myanmar. *Water*. **14**, 3434. https://doi.org/10.3390/w14213434 (2022).
103. Lyu, H., Tian, F., Zhang, K. & Nan, Y. Water-energy-food nexus in the Yarlung Tsangpo-Brahmaputra river basin: Impact of mainstream hydropower development. *J. Hydrol. : Reg. Stud.* **45**, 101293. https://doi.org/10.1016/j.ejrh.2022.101293 (2023).
104. Mabhaudhi, T. et al. The water–energy–food nexus as a tool to transform rural livelihoods and well-being in southern Africa. *Int. J. Environ. Res. Public. Health*. **16**, 2970. https://doi.org/10.3390/ijerph16162970 (2019).
105. McNabola, A., Mérida García, A. & Rodríguez Díaz, J. A. The role of micro-hydropower energy recovery in the water-energy-food nexus. *Environ. Sci. Proceedings*. 21, 27; (2022). https://doi.org/10.3390/environsciproc2022021027
106. Nasrollahi, H., Shirazizadeh, R., Shirmohammadi, R., Pourali, O. & Amidpour, M. Unraveling the water-energy-food-environment nexus for climate change adaptation in Iran: Urmia lake basin case study. *Water*. **13**, 1282. https://doi.org/10.3390/w13091282 (2021).
107. Niva, V., Cai, J., Taka, M., Kummu, M. & Varis, O. China's sustainable water-energy-food nexus by 2030: Impacts of urbanization on sectoral water demand. *J. Clean. Prod.* **251**, 119755. https://doi.org/10.1016/j.jclepro.2019.119755 (2020).
108. Opoku, E. K. et al. Quantifying and analysing water trade-offs in the water-energy-food nexus: The case of Ghana. *Water-Energy Nexus*. **5**, 8–20. https://doi.org/10.1016/j.wen.2022.06.001 (2022).
109. Ouyang, Y., Cai, Y., Xie, Y., Yue, W. & Guo, H. Multi-scale simulation and dynamic coordination evaluation of water-energy-food and economy for the Pearl River delta city cluster in China. *Ecol. Indic.* **130**, 108155. https://doi.org/10.1016/j.ecolind.2021.108155 (2021).
110. Radini, S. et al. Urban water-energy-food-climate nexus in integrated wastewater and reuse systems: cyber-physical framework and innovations. *Appl. Energy*. **298**, 117268. https://doi.org/10.1016/j.apenergy.2021.117268 (2021).
111. Ravar, Z., Zahraie, B., Sharifinejad, A., Gozini, H. & Jafari, S. System dynamics modeling for assessment of water–food–energy resources security and nexus in Gavkhuni basin in Iran. *Ecol. Indic.* **108**, 105682. https://doi.org/10.1016/j.ecolind.2019.105682 (2020).

112. Saray, M. H. et al. Optimization of water-energy-food nexus considering CO2 emissions from cropland: a case study in northwest Iran. *Appl. Energy*. **307**, 118236. https://doi.org/10.1016/j.apenergy.2021.118236 (2022).
113. Shu, Q., Scott, M., Todman, L. & McGrane, S. J. Development of a prototype composite index for resilience and security of water-energy-food (wef) systems in industrialised nations. *Environ. Sustain. Indic.* **11**, 100124. https://doi.org/10.1016/j.indic.2021.100124 (2021).
114. Spiegelberg, M. et al. Unfolding livelihood aspects of the water–energy–food nexus in the dampalit watershed, Philippines. *J. Hydrol. : Reg. Stud.* **11**, 53–68. https://doi.org/10.1016/j.ejrh.2015.10.009 (2017).
115. Vaidya, B., Shrestha, S. & Ghimire, A. Water footprint assessment of food-water-energy systems at Kathmandu university, Nepal. *Curr. Res. Environ. Sustain.* **3**, 100044. https://doi.org/10.1016/j.crsust.2021.100044 (2021).
116. Zeng, Y. et al. A system dynamic model to quantify the impacts of water resources allocation on water–energy–food–society (wefs) nexus. *Hydrol. Earth Syst. Sci.* **26**, 3965–3988. https://doi.org/10.5194/hess-26-3965-2022 (2022).
117. Zhang, F., Cai, Y., Tan, Q., Engel, B. A. & Wang, X. An optimal modeling approach for reducing carbon footprint in agricultural water-energy-food nexus system. *J. Clean. Prod.* **316**, 128325. https://doi.org/10.1016/j.jclepro.2021.128325 (2021a).
118. Haghjoo, R., Choobchian, S., Morid, S. & Abbasi, E. Development and validation of management assessment tools considering water, food, and energy security nexus at the farm level. *Environ. Sustain. Indic.* **16**, 100206. https://doi.org/10.1016/j.indic.2022.100206 (2022).
119. Haghjoo, R., Choobchian, S., Morid, S. & Abbasi, E. Indicators of water, food and energy security nexus approach in agriculture: application of content analysis. *Iran. J. Agri Econ. Dev. Res.* **54**, 261–291. https://doi.org/10.22059/ijaedr.2022.342410.669145 (2023).
120. Harwood, S. A. In search of a (wef) nexus approach. *Environ. Sci. Policy*. **83**, 79–85. https://doi.org/10.1016/j.envsci.2018.01.020 (2018).
121. Kaddoura, S. & El Khatib, S. Review of water-energy-food nexus tools to improve the nexus modelling approach for integrated policy making. *Environ. Sci. Policy*. **77**, 114–121. https://doi.org/10.1016/j.envsci.2017.07.007 (2017).
122. Karnib, A. Bridging science and policy in water-energy-food nexus: using the Q-nexus model for informing policy making. *Water Resour. Manage.* **32**, 4895–4909. https://doi.org/10.1007/s11269-018-2059-5 (2018).
123. Lazaro, L. L. B., Bellezoni, R. A., Puppim de Oliveira, J. A., Jacobi, P. R. & Giatti, L. L. Ten years of research on the water-energy-food nexus: an analysis of topics evolution. *Front. Water*. **4**, 859891. https://doi.org/10.3389/frwa.2022.859891 (2022).
124. Li, M. et al. An optimal modelling approach for managing agricultural water-energy-food nexus under uncertainty. *Sci. Total Environ.* **651**, 1416–1434. https://doi.org/10.1016/j.scitotenv.2018.09.291 (2019c).
125. Mannschatz, T., Wolf, T. & Hülsmann, S. Nexus tools platform: web-based comparison of modelling tools for analysis of water-soil-waste nexus. *Environ. Model. Softw.* **76**, 137–153. https://doi.org/10.1016/j.envsoft.2015.10.031 (2016).
126. Martinez, P., Blanco, M. & Castro-Campos, B. The water–energy–food nexus: a fuzzy-cognitive mapping approach to support nexus-compliant policies in Andalusia (Spain). *Water*. **10**, 664. https://doi.org/10.3390/w10050664 (2018).
127. Norouzi, N. Presenting a conceptual model of water-energy-food nexus in Iran. *Curr. Res. Environ. Sustain.* **4**, 100119. https://doi.org/10.1016/j.crsust.2021.100119 (2022).
128. Purwanto, A., Sušnik, J., Suryadi, F. & de Fraiture, C. Using group model building to develop a causal loop mapping of the water-energy-food security nexus in Karawang regency, Indonesia. *J. Clean. Prod.* **240**, 118170. https://doi.org/10.1016/j.jclepro.2019.118170 (2019).
129. Wicaksono, A. & Kang, D. Nationwide simulation of water, energy, and food nexus: case study in South Korea and Indonesia. *J. Hydro-environ Res.* **22**, 70–87. https://doi.org/10.1016/j.jher.2018.10.003 (2019).
130. Zarei, M. The water-energy-food nexus: a holistic approach for resource security in Iran, Iraq, and Turkey. *Water-Energy Nexus*. **3**, 81–94. https://doi.org/10.1016/j.wen.2020.05.004 (2020).
131. Song, S. et al. Indicator-based assessments of the coupling coordination degree and correlations of water-energy-food-ecology nexus in Uzbekistan. *J. Environ. Manage.* **345**, 118674. https://doi.org/10.1016/j.jenvman.2023.118674 (2023).
132. Rai, P. K. Lalawmpuii. Role of water-energy-food nexus in environmental management and climate action. *Energy Nexus.* 11, 100230; (2023). https://doi.org/10.1016/j.nexus.2023.100230
133. Akbari Variani, H., Afshar, A., Vahabzadeh, M. & Molajou, A. A review on food subsystem simulation models for the water-food-energy nexus: development perspective. *Environ. Sci. Pollut Res.* **30**, 95197–95214. https://doi.org/10.1007/s11356-023-29149-6 (2023).
134. Laspidou, C. S., Mellios, N. K., Spyropoulou, A. E., Kofinas, D. T. & Papadopoulou, M. P. Systems thinking on the resource nexus: modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions. *Sci. Total Environ.* **717**, 137264. https://doi.org/10.1016/j.scitotenv.2020.137264 (2020).
135. Martinez-Hernandez, E., Leach, M. & Yang, A. Understanding water-energy-food and ecosystem interactions using the nexus simulation tool NexSym. *Appl. Energy*. **206**, 1009–1021. https://doi.org/10.1016/j.apenergy.2017.09.022 (2017).
136. Vahabzadeh, M., Afshar, A., Molajou, A., Parnoon, K. & Ashrafi, S. M. A comprehensive energy simulation model for energy-water-food nexus system analysis: a case study of the great Karun water resources system. *J. Clean. Prod.* **418**, 137977. https://doi.org/10.1016/j.jclepro.2023.137977 (2023).
137. Valencia-Marquez, D. et al. Multi-objective and machine learning strategies for addressing the water–energy–waste nexus in the design of energy systems. *Sustainable Energy Technol. Assess.* **60**, 103445. https://doi.org/10.1016/j.seta.2023.103445 (2023).
138. Fox-Kämper, R. et al. The role of urban agriculture in food-energy-water nexus policies: insights from Europe and the US. *Landsc. Urban Plann.* **239**, 104848. https://doi.org/10.1016/j.landurbplan.2023.104848 (2023).
139. Mondal, K., Chatterjee, C. & Singh, R. Examining the coupling and coordination of water-energy-food nexus at a sub-national scale in India: insights from the perspective of sustainable development goals. *Sustainable Prod. Consum.* **43**, 140–154. https://doi.org/10.1016/j.spc.2023.10.020 (2023).
140. Mperejekumana, P. et al. Integrating climate change adaptation into water-energy-food-environment nexus for sustainable development in east African community. *J. Clean. Prod.* **434**, 140026. https://doi.org/10.1016/j.jclepro.2023.140026 (2024).
141. Adeola, O. M. et al. Review of publications on the water-energy-food nexus and climate change adaptation using bibliometric analysis: a case study of Africa. *Sustainability*. **14**, 13672. https://doi.org/10.3390/su142013672 (2022).
142. Ma, N., Zhang, Y., Zhang, R., Zhang, W. & Li, X. Comprehensive review of food-energy-water nexus at the community scale. *J. Clean. Prod.* **420**, 138311. https://doi.org/10.1016/j.jclepro.2023.138311 (2023).
143. Vargas, D. C. M., Hoyos, C. P. Q. & Manrique, O. L. H. The water-energy-food nexus in biodiversity conservation: a systematic review around sustainability transitions of agricultural systems. *Heliyon*. **9**, e17016. https://doi.org/10.1016/j.heliyon.2023.e17016 (2023).
144. Jin, X., Jiang, W., Fang, D., Wang, S. & Chen, B. Evaluation and driving force analysis of the water-energy–carbon nexus in agricultural trade for RCEP countries. *Appl. Energy*. **353**, 122143. https://doi.org/10.1016/j.apenergy.2023.122143 (2024).
145. Ramírez-Márquez, C. & Ponce-Ortega, J. M. Process systems engineering tools for the water–energy–food nexus: challenges and opportunities. *Curr. Opin. Chem. Eng.* **42**, 100980. https://doi.org/10.1016/j.coche.2023.100980 (2023).
146. Huan, S. & Liu, X. Network modeling and stability improvement of the water-energy-fertilizer-food nexus flows based on global agricultural trade. *Sustainable Prod. Consum.* **39**, 480–494. https://doi.org/10.1016/j.spc.2023.05.034 (2023).
147. Zhou, Y., Zhang, X., Chen, Y., Xu, X. & Li, M. A water-land-energy-carbon nexus evaluation of agricultural sustainability under multiple uncertainties: the application of a multi-attribute group decision method determined by an interval-valued intuitionistic fuzzy set. *Expert Syst. Appl.* **242**, 122833. https://doi.org/10.1016/j.eswa.2023.122833 (2024).

148. Wang, Y. et al. Supply-demand risk assessment and multi-scenario simulation of regional water-energy-food nexus: a case study of the Beijing-Tianjin-Hebei region. *Resour. Conserv. Recycl.* **174**, 105799. https://doi.org/10.1016/j.resconrec.2021.105799 (2021b).
149. Lazaro, L. L. B., Giatti, L. L. & de Oliveira, J. A. P. Water-energy-food nexus approach at the core of businesses: how businesses in the bioenergy sector in Brazil are responding to integrated challenges? *J. Clean. Prod.* **303**, 127102. https://doi.org/10.1016/j.jclepro.2021.127102 (2021b).
150. Karami, S., Karami, E., Buys, L. & Drogemuller, R. System dynamic simulation: a new method in social impact assessment (sia). *Environ. Impact Assess. Rev.* **62**, 25–34. https://doi.org/10.1016/j.eiar.2016.07.009 (2017).

Author contributions

A: E.F.: Gathered and analyzed the primary data and wrote a draft of the manuscript. B: S.C.: Study design and Supervision, Writing - Review & Editing.C: S.K.: Methodology, Review & Editing. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Informed consent

Informed consent was obtained from all subjects and/or their legal guardian(s).

Additional information

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