ENVIRONMENTAL RESEARCH
LETTERS

TOPICAL REVIEW • OPEN ACCESS

# A review of water-energy-food-ecosystems Nexus research in the Mediterranean: evolution, gaps and applications

To cite this article: Enrico Lucca *et al* 2023 *Environ. Res. Lett.* **18** 083001

View the article online for updates and enhancements.

ENVIRONMENTAL RESEARCH
LETTERS

CrossMark

OPEN ACCESS

RECEIVED
13 April 2023

REVISED
12 June 2023

ACCEPTED FOR PUBLICATION
3 July 2023

PUBLISHED
18 July 2023



TOPICAL REVIEW

# A review of water-energy-food-ecosystems Nexus research in the Mediterranean: evolution, gaps and applications

**Enrico Lucca**[1], **Jerome El Jeitany**[2,3,*], **Giulio Castelli**[1,4,5], **Tommaso Pacetti**[2], **Elena Bresci**[1], **Fernando Nardi**[6,7] **and Enrica Caporali**[2]

1 Department of Agriculture, Food, Environment and Forestry (DAGRI), Università degli Studi di Firenze, Via San Bonaventura, 13, Firenze 50145, Italy
2 Department of Civil and Environmental Engineering (DICEA), Università degli Studi di Firenze, Via di S. Marta, 3, Firenze 50139, Italy
3 Technische Universität Braunschweig, Landscape Ecology and Environmental Systems Analysis, Institute of Geoecology, Langer Kamper Street, 19c, Braunschweig, Germany
4 UNESCO Chair in Hydropolitics, University of Geneva, Bd Carl-Vogt 66, 1205 Genève, Switzerland
5 Environmental Governance and Territorial Development Hub (GEDT), University of Geneva, Bd Carl-Vogt 66, 1205 Genève, Switzerland
6 WARREDOC, University for Foreigners of Perugia, Perugia 06123, Italy
7 Institute of Environment (InWE), Florida International University, Miami, FL 33199, United States of America
* Author to whom any correspondence should be addressed.

**E-mail:** jerome.eljeitany@unifi.it

**Keywords:** WEFE Nexus, sustainability, clean technology, natural resources management

Supplementary material for this article is available online

## Abstract

The water-energy-food-ecosystems (WEFE) Nexus has gained recognition as an innovative approach for analysing the interconnectedness of global resource systems and achieving sustainability goals. In the Mediterranean, where water scarcity, climate change, and ecosystem degradation pose significant challenges, implementing an integrated WEFE Nexus approach is crucial. We conducted a comprehensive review of scientific literature through the lenses of Nexus 'ideas', 'relationship' and 'practices'. A total of 142 research articles were selected and characterized in terms of WEFE interlinkages being investigated, explored topics, methods and scales of analysis, and contexts of operationalization. We found that water-energy interdependences dominate WEFE Nexus research in the Mediterranean, driven by the large presence of energy-intensive water abstraction and distribution systems to meet drinking and irrigation water demands. At the same time, the expansion of the Nexus approach to additional components is only partial, mostly focusing on assessing impacts on the physical environment and climate, without capturing feedback dynamics. Geographically, Nexus research in the Mediterranean is primarily conducted in isolated case studies, with few large scale assessments developed at the entire Mediterranean scale, and with some countries not yet represented, in particular the Western Balkans. Although WEFE Nexus research in the Mediterranean is recognizing the importance of transdisciplinarity moving beyond biophysical assessments to encompass societal and governance dynamics, further research is needed on understanding the economic implications of WEFE Nexus interactions. To advance Nexus implementation in the region, sustainable technology, and natural resources management, which are key fields of WEFE Nexus research operationalization, would benefit from harmonization in their design objectives. This would enable a more comprehensive and coherent approach towards achieving water, food, and energy security while preserving the environment in the Mediterranean region.

## 1. Introduction

While the concept of integrated resources management acknowledges the prevailing dynamics between the several resources examined (Florin and Gabriel 1991, Pahl-Wostl 2007, Rockström *et al* 2009), the emergence of the Nexus[8] approach (Hoff 2011) during the last decade highlighted the importance of accounting for these dynamics, with a specific emphasis on the interconnectedness present when dealing with the management of water, energy, and food (Ringler *et al* 2013). One of the earliest explicit introductions of the Nexus approach sprung in parallel with the debate on the sustainability of biofuel production as an energy source promoting reduction in carbon emissions (Bauen *et al* 2015). Nexus based studies pointed out how the land use change impact induced by the cultivation of crops used in biofuels could be in conflict with availability of land for food production, could increase water consumption and determine an expansion of agricultural activities contradicting the desired reduction in emissions (Moioli *et al* 2018, Viccaro *et al* 2022).

Hence, the Nexus approach acknowledges the mutual interlinkages between water, energy and food, and calls for the creation of systems that maximise synergies and minimise trade-offs among sectoral needs to optimise the sustainable management of natural resources and to improve resource use efficiency (Bazilian *et al* 2011). Embracing such a holistic approach in lieu of a silo sectorial thinking could help create integrated solutions for the achievement of the Sustainable Development Goals (Carmona-Moreno *et al* 2021). Even more so in the Mediterranean, a region of the world characterised by severe threats of water scarcity, increasing food and energy demands and degradation of natural ecosystems. Indeed, climate projections for the Mediterranean clearly point to this region as a hotspot of change, with rates of warming and reduction in precipitation above the global average, especially in the southern and eastern Mediterranean countries (Lionello and Scarascia 2018). The anticipated changes in temperature, precipitation, sea level and in the frequency of droughts and floods will combine with existing environmental and socio-economic pressures, i.e., population growth, conflicts, water pollution, potentially leading to severe impacts for water security, food security, ecosystems health, and ultimately human security (Cramer *et al* 2018). The Union for the Mediterranean (UfM) placed the water-energy-food-ecosystems (WEFE) Nexus at the heart of their Water Policy Framework for Actions 2030 to increase the resilience against such compound risks and to promote social stability, suggesting interventions at local and regional scales, including Nexus assessments, multi-stakeholder policy dialogues, testing of Nexus pilot applications and leveraging finance for scaling up Nexus solutions (Union for the Mediterranean 2020). Research and innovation are key enablers of such a transformation, since they can help understand the complexity of Nexus interactions, demonstrate the benefits of adopting a Nexus approach and provide evidence for informed decision making. In such a context, the Partnership for Research & Innovation in the Mediterranean (PRIMA) Foundation introduced in 2019 the WEFE Nexus as a new thematic stream of funding to mobilise researchers, stakeholders and innovators from the Euro-Mediterranean region and advance Nexus implementation (Riccaboni *et al* 2022). However, a comprehensive review of whether current research across the Mediterranean is aligned with the pressing need of adopting such an integrated approach in managing and governing natural resources is yet to be produced. In fact, assessments of Nexus implementation across the region have to date focused on reviewing projects' case studies (Hoff *et al* 2019, Malagó *et al* 2021), analysing policies and legislations (Bazzana *et al* 2023) and gathering regional experts' opinions (Markantonis *et al* 2019). No studies have investigated outputs of scientific research specific to the region.

Numerous literature reviews on Nexus research at the global scale exist and they have all emphasised the emergence of a large diversity of definitions, design objectives, modelling approaches and applications (Albrecht *et al* 2018, Galaitsi *et al* 2018, Purwanto *et al* 2021, Taguta *et al* 2022). However, only by adopting a geographical focus in the review process, main drivers, key traits, and limitations of Nexus research in a specific region can be identified. The goal of this review article is, therefore, to assess Nexus research in the Mediterranean in terms of critical interlinkages being investigated, explored topics, methods and scales of analysis, and context of application. In doing so, research gaps and possible future directions for research in the Mediterranean are revealed and, secondly, compared against other regional and global findings. Moreover, we deliberately expand the review to the fourth 'Ecosystem' component, the WEFE Nexus, to align with the recent research priority given to integrating natural ecosystems and their services into the Nexus approach (Hülsmann *et al* 2019). Nexus researchers and practitioners interested in understanding the methodological approaches that address the WEFE Nexus in the Mediterranean are considered the major audience of this review.

## 2. Methodology

Figure 1 illustrates the procedure adopted in this study for the review of scientific literature on the WEFE Nexus in the Mediterranean. It consisted of

[8] Nexus: 'a connection or series of connections linking two or more things' (The Cambridge English Dictionary).

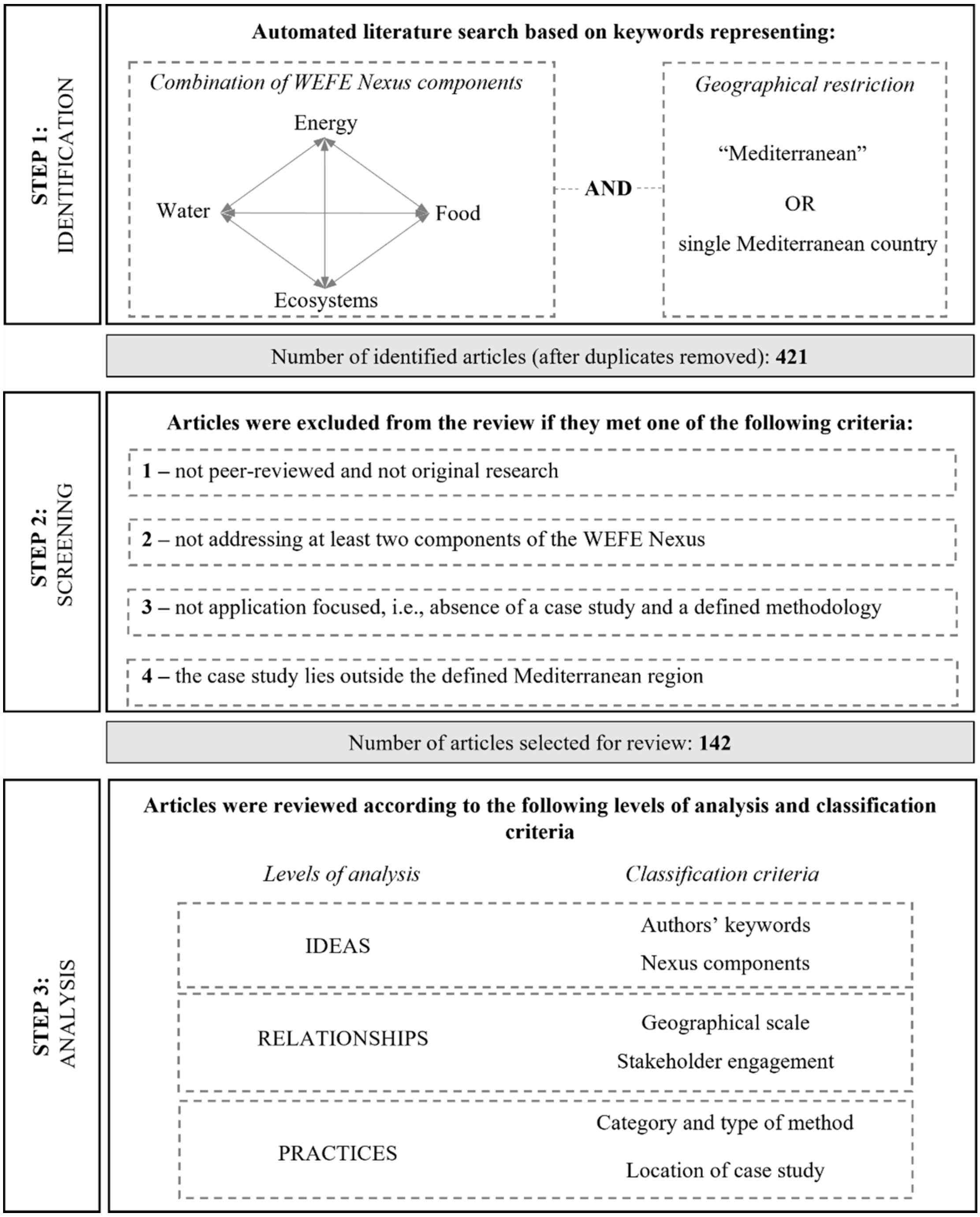


**Figure 1.** Procedure adopted for the identification, screening, and analysis of scientific articles on the water-energy-food-ecosystems (WEFE) Nexus in the Mediterranean.

three steps: (i) identification of articles from research databases, (ii) screening of the identified articles based on exclusion criteria and (iii) analysis of the selected articles. Step 1 'identification' and Step 2 'screening' followed the PRISMA guidelines for conducting meta-analyses (Page *et al* 2021), while in Step 3 the integrative review approach presented by Snyder (2019) was adopted to complement the aim of understanding the evolution of Nexus research in the Mediterranean in terms of ideas, relationships, and practices.

### 2.1. Step 1: Identification of articles

At Step 1, peer-reviewed articles were identified from SCOPUS and Web of Science database by performing multiple search queries in the title, abstract and keywords of the database articles. The terms of each query consisted of keywords representing the multiple possible combinations that can be obtained from the components of the WEFE Nexus, e.g., water-energy Nexus, energy-food-water Nexus, water-energy-food Nexus, and the list of the Mediterranean countries, or the word 'Mediterranean'. All countries surrounding the Mediterranean Sea and Portugal constituted the list of Mediterranean countries: Spain, France, Monaco, Italy, Slovenia, Croatia, Bosnia-Herzegovina, Montenegro, Albania, Greece, Turkey, Syria, Lebanon, Palestine, Israel, Egypt, Libya, Algeria, Tunisia, Morocco, Cyprus, Malta, and Portugal. The term 'resource Nexus' was also used in combination with the geographical restriction to identify articles that studied the Nexus among natural resources without explicitly mentioning the WEFE Nexus components. The search was limited to peer-reviewed articles published in the English language from 2011 onwards. The use of an application programming interface and the pybliometrics 3.4.0 Python package (Rose and Kitchin 2019) allowed direct access to the SCOPUS database and the automated retrieval of articles based on the set search queries. Retrieval of articles from Web of Science was performed manually. The last search query was carried out on 31/10/2022 and produced a total of 421 articles.

### 2.2. Step 2: Screening of identified articles

The articles identified in Step 1 were screened based on four exclusion criteria to ensure that the review focused only on articles pertinent to understanding the emergence and operationalization of the WEFE Nexus approach in the Mediterranean region. Firstly, we included only peer-reviewed and original research, therefore excluding review articles and those book chapters and conference articles whose research content was replicated in other articles. Secondly, we focused on articles explicitly analysing interconnections among water, energy, food, and ecosystems. In general, most studies that address synergies and trade-offs between any two components, hold the potential to be labelled as a Nexus study. Therefore, we avoided any ambiguity by selecting the articles that explicitly addressed interconnections between at least two of the four WEFE Nexus components. Thirdly, the assessment of the practicality of academic research on the WEFE Nexus was ensured by excluding articles without a defined methodology and application in a case study. Lastly, articles whose case study fell outside the defined Mediterranean region were not considered in the review. The application of the exclusion criteria described above led to the selection of 142 articles.

#### *2.2.1. Definition of Mediterranean region*

There is no single definition of the Mediterranean region (Merheb *et al* 2016) and the delimitation of Mediterranean boundaries in WEFE Nexus applications is even more difficult given the spatial heterogeneity of the WEFE Nexus components. While hydrological applications adopt a catchment area definition, ecological studies expand such limits to entail a bigger bio-climatic zone (UNESCO and FAO 1963). From an economic and political perspective, the region may also be defined through the administrative boundaries of countries surrounding the Mediterranean Sea (PNUE/PAM-Plan Bleu 2009). Adopting a single definition of the Mediterranean region in the context of WEFE Nexus research is also challenged by the various spatial scales addressed by Nexus assessments, ranging from local to national and international. Thus, in the absence of a systematic definition of Mediterranean and of a WEFE Nexus study scale, we adopted a two-faceted definition of the Mediterranean region. For all studies addressing the WEFE Nexus at the sub-national scale, we considered the union between the Mediterranean bioclimate limit and the Mediterranean catchment basin, with the exclusion of the Nile River. The Nile River basin was excluded in our analysis since most of the discharge of the Nile in Egypt comes from runoff generated in the equatorial lake regions and Ethiopia (Elsayed *et al* 2022), areas which we do not deem Mediterranean from a bioclimatic, hydrological, and administrative perspective. Thus, for the country of Egypt, we considered Mediterranean those case studies that fall within the area draining into the Mediterranean Sea or that are hydrologically disconnected from the Nile River. For studies addressing the WEFE Nexus at the national or international level, we considered as Mediterranean all the countries surrounding the Mediterranean Sea with the addition of Portugal. By doing so, a bigger geographical extent is adopted that allows to identify whether the WEFE Nexus is dealt with as a water-related problem (hence focused on water catchments areas) or crosses these boundaries with the integration of elements like ecosystems, and trade-offs with exogenous factors emerging at a larger scale. The definition of both bioclimatic limit and catchment area is adopted from the Plan Bleu (PNUE/PAM-Plan Bleu 2009).

### 2.3. Step 3: Analysis of screened articles

In Step 3, the 142 selected articles were reviewed based on three different levels of analysis and six classification criteria to provide a qualitative and quantitative representation of the results. This is in accordance with the integrative approach stated by Snyder (2019), suitable for emerging cross-cutting topics, such as the water-energy-food Nexus. The levels of analysis were 'ideas', 'relationships', and 'practices', and these were revealed by classifying each article based on six criteria, described in table 1. The initial indication of 'ideas' in WEFE Nexus research emerges from the keywords used by the author to describe their article and by the specific Nexus components being addressed, e.g., water-food, energy-ecosystems, WEFE. 'Relationships' instead depict in this review the various geographic scales of analysis adopted in each article, spanning from the micro scale (i.e., building, field) to the entire Mediterranean region. Within 'relationships', the focus is also put on the interactions between authors and the local social

**Table 1.** The analysis framework adopted for the review of selected articles on the water-energy-food-ecosystems Nexus. For each classification criteria, the reader is directed to the corresponding section of the review article.

| Classification criteria | | | Description |
|---|---|---|---|
| Level of analysis | Ideas | Keywords (section 3.2) | Article's keywords as provided by the authors |
| | | Nexus components (section 3.3) | Combination of Nexus components (e.g., water-energy, water-energy-food, energy-food) analysed in the article. In most cases Nexus components were explicitly defined by the authors in the abstract or title, otherwise they were assigned based on the Nexus relationships being examined |
| | Relationships | Geographical scale (section 3.4) | The scale of analysis at which the research is conducted: micro (e.g., building, farm), local (region, city), river basin, national and multinational |
| | | Stakeholder engagement (section 3.6) | Levels of stakeholder engagement adopted in the research, ranging from 0 to 3:<br>0—no engagement,<br>1—information and data collection,<br>2—co-definition of Nexus challenges and interlinkages,<br>3—co-creation of methods, knowledge, and solutions for the Nexus |
| | Practices | Location of case studies (section 3.4) | Detailed location information (e.g., coordinates, name of city, region) of all case studies to enable mapping |
| | | Methods (section 3.5) | Category, i.e., quantitative, qualitative, and type of methods used for research |

context, defined as degree of stakeholder engagement, which ranges from no interaction (value = 0) to the co-creation of methods and knowledge (value = 3). The role of stakeholder engagement in enhancing transdisciplinarity in Nexus research has been widely recognised, but it remains fairly limited in practice (Hoolohan *et al* 2018). Hence, the adoption of the 'stakeholder engagement' criteria to understand whether researchers in the Mediterranean region are involving stakeholders in WEFE Nexus analysis. Finally, 'practices' examine the various methods used in WEFE Nexus assessment and the distribution of case studies across the region to evaluate the current extent of WEFE Nexus research operationalization and its methodological approaches.

### 2.4. Data visualization

The results of the analysis were presented using a suite of visualization tools including bar plots, pie charts, network diagram and Sankey diagrams. Bar plots and pie charts were created with ggplot2 package in R (Wickham 2016, R Core Team 2022), while VOSViewer software (van Eck and Waltman 2010) was used to produce the network diagram visualizing the co-occurrence of the articles' keywords. The network diagram is composed of vertices, representing the single keywords, and of links representing the co-occurrence of two keywords in the same article. To limit the hairball effect, keywords occurring in less than four articles were excluded from the diagram. Finally, Sankey diagrams were created using ggsankey package in R and used to visualize the distribution of the reviewed literature across the classification criteria.

## 3. Results

### 3.1. Year and journal of publication

Figure 2 illustrates the number of articles published on the Nexus in the Mediterranean from 2011 to the end of October 2022, together with the number of articles reviewed in this study. A steep increase in Nexus research is observed from 2015 onwards, four years after the affirmation of the water-energy-food security Nexus at the Bonn2011 Nexus Conference (Hoff 2011). While initially research focused on the relationships between water and energy consumption in irrigated agriculture (Soto-García *et al* 2013, Martin-Gorriz *et al* 2014), later the scope of investigation broadened to a variety of activities within the water, energy, and food sectors. This is in line with an increased attention paid globally to the Nexus theme in the field of natural resources management (Fernandes Torres *et al* 2019), and it contributed to a dispersion of Nexus research in the Mediterranean across a large number of journals, figure 3.

In fact, the 142 reviewed articles were published in 76 different journals, 70% of which contained only one article (figure 3(a)). Only *Water* and *Sustainability* counts more than eight articles each, followed by two journals in the field of Environmental Science, i.e., *Science of the Total Environment* and *Journal of Cleaner Production*, and two journals in the field of Energy, i.e., *Applied Energy* and *Renewable*

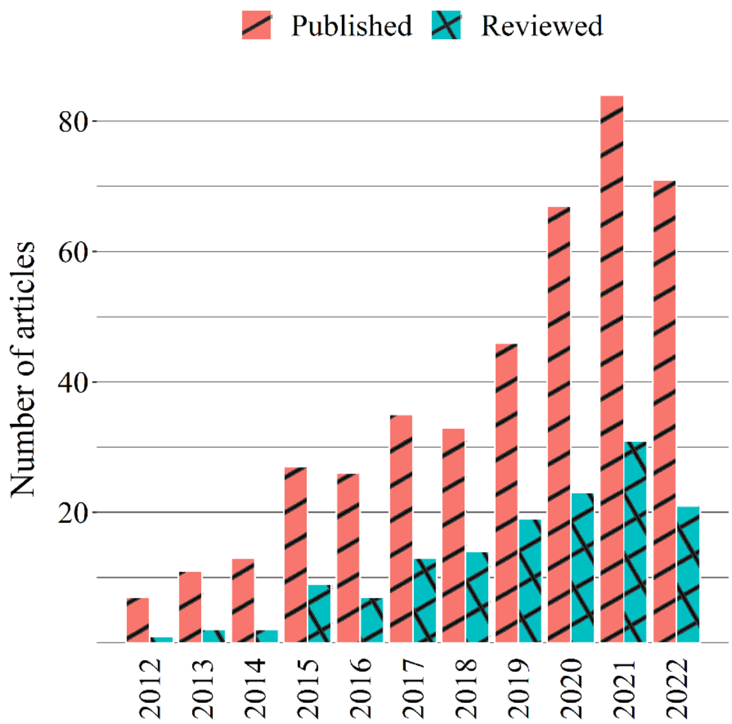


**Figure 2.** Number of articles published (striped) and reviewed (hatched) on the Nexus in the Mediterranean, per year, from 2011 to October 2022.

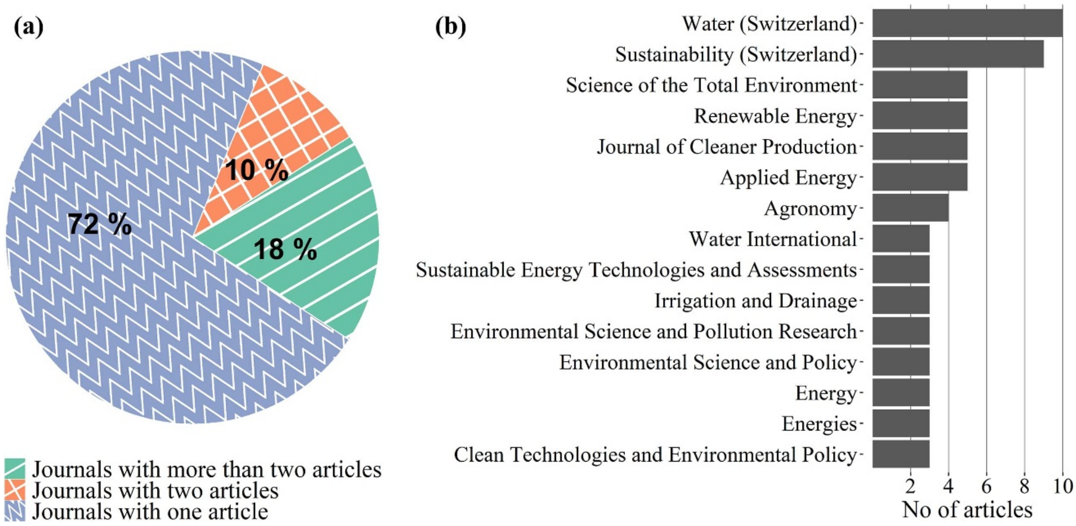


**Figure 3.** Overview of journals targeted by the reviewed articles: (a) percentage of journals containing one, two or more articles; (b) list of journals containing at least three articles.

*Energy*, all with five articles each (figure 3(b)). *Agronomy* comes after, with 4 articles.

### 3.2. Keywords

Whilst 501 different keywords were used by the authors of the reviewed articles to describe their research on the Nexus in the Mediterranean, we focused on the authors' keywords that re-occurred at least four times, i.e., a group of 19 terms. Figure 4 shows the frequency of occurrence of the 19 keywords and the intensity of their co-occurrence. The most frequently used keywords were water-energy Nexus, water-energy-food Nexus, sustainability, and Nexus. There is a clear bipolarization around the concepts of water-energy Nexus and water-energy-food Nexus, creating two distinct, but interconnected, groups of keywords. Both water-energy-food and water-energy Nexus are linked with water scarcity and climate change, highlighted in the reviewed literature as main drivers for an integrated management of natural resources in the Mediterranean, and with sustainability, the ultimate goal of adopting a Nexus approach.

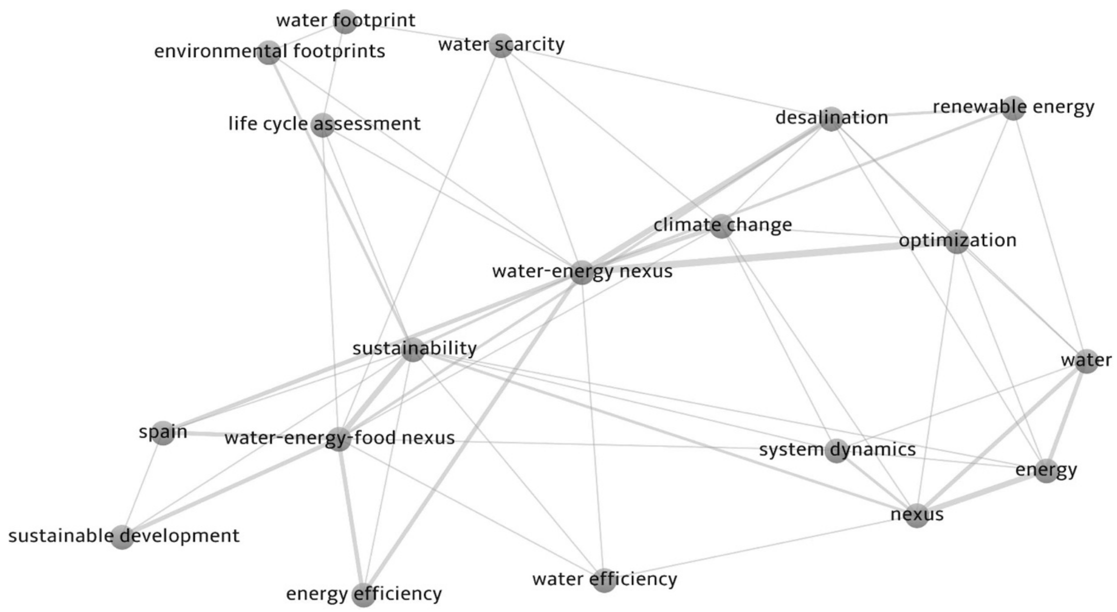


**Figure 4.** Author's keywords co-occurrence network. The size of the label and circle is proportional to the number of the reviewed articles in which the keyword occurred. Line thickness is proportional to the number of times two keywords occurred together.

Water efficiency and energy efficiency arise in the keywords' cloud as concrete outcomes from the promotion of a Nexus approach to achieve sustainability. Desalination is the only process within the water, energy and food supply chains that appears in the authors' keywords map, highlighting the centrality of this source of water for the Mediterranean region. Desalination is strongly linked with water-energy Nexus and renewable energy, as innovative solutions are being sought to make this process more environmentally and economically feasible (Eltawil *et al* 2009). The keyword sustainability acts as a bridge between the three Nexus groups and a cluster of keywords representing the pressure of human activities on the environment, i.e., life cycle assessment (LCA), environmental footprints. Yet, the ecosystem component of the WEFE Nexus does not emerge in the map of the 19 most frequently used keywords, nor do other terms frequently associated with it, such as biodiversity, environment, and natural resources.

Research methods commonly used to analyse the Nexus in the Mediterranean stand out as recurring keywords in the reviewed articles and these include footprinting, LCA, system dynamics and optimization techniques.

### 3.3. Nexus components

Table 2 presents the combinations of WEFE Nexus components identified in the reviewed literature. As shown by the keywords network diagram, water-energy and water-energy-food Nexus are the most recurring arrangements accounting for 69% of the reviewed articles and followed by WEFE, energy-food, and water-energy-food-land-climate, with 4% each.

**Table 2.** Percentage of articles analysing the listed combination of Nexus components.

| Combination of Nexus components | % |
|---|---|
| Water-energy | 38 |
| Water-energy-food | 31 |
| Water-energy-food-ecosystems | 4 |
| Energy-food | 4 |
| Water-energy-food-land-climate | 4 |
| Water-energy-food-climate | 3 |
| Water-energy-food-land | 3 |
| Water-food | 3 |
| Water-food-climate | 2 |
| Energy-ecosystems | 2 |
| Energy-food-climate | <1 |
| Energy-land-ecosystems | <1 |
| Land-food | <1 |
| Water-ecosystems | <1 |
| Water-ecosystems-climate | <1 |
| Water-energy-climate | <1 |
| Water-energy-ecosystems | <1 |
| Water-energy-land | <1 |
| Water-energy-land-climate | <1 |
| Water-food-ecosystems-climate | <1 |
| Water-waste-energy | <1 |

#### *3.3.1. Water-energy*

The bidirectional relations among water and energy are extensively studied by Nexus research in the Mediterranean, with the intent of identifying hotspot of resource use and testing options for improved resource efficiency. On the one hand, consumption of energy associated with supplying water for both domestic and agricultural use was quantified. Arfelli *et al* (2022) and Yoon *et al* (2018) provided a comprehensive evaluation of energy use in the urban water cycle, while other articles focused on single processes within it: water withdrawal (Bertsiou and Baltas 2022) and treatment (Calise *et al* 2020), water distribution (Lenzi *et al* 2013), end-use in buildings (Barberán *et al* 2019, Yoon *et al* 2022) and wastewater treatment (Odabaş Baş and Aydınalp Köksal 2022). For the agricultural sector, the long-term evolution of energy use associated with irrigation was analysed by Espinosa-Tasón *et al* (2020) and Martin-Gorriz *et al* (2014) for Spain, revealing the impact of irrigation expansion, infrastructures modernization and the introduction of non-conventional water resources on energy consumption for pumping and treatment. On the other hand, freshwater consumption associated with energy production was quantified at the national level for Italy (Miglietta *et al* 2018), Spain (Tovar-Facio *et al* 2021) and Greece (Ziogou and Zachariadis 2017), while other studies provided a more detailed investigation of water use for a specific source of energy: nuclear (Sesma-Martín and Rubio-Varas 2019), hydropower (Branche 2017, Solera *et al* 2018, Bonato *et al* 2019) and traditional thermal power plants (Fernández-Blanco *et al* 2017). Fewer articles captured water-energy interdependencies simultaneously. In this direction, Khan *et al* (2018) developed a new model linking Spanish water and energy systems across scales and throughout the life cycle of each resource to provide insights into cross-sectoral impacts of climate and socio-economic scenarios.

Beyond characterising interlinkages among water and energy supply chains, water-energy Nexus research in the Mediterranean also dealt with the analysis of coupled water-energy technologies. Desalination plants run by renewable energies were widely studied energy to water systems with the aim of optimising their performance and of analysing their techno-enviro-economic feasibility for Mediterranean islands and coastal areas (wind energy; Bertsiou and Baltas 2022; solar energy: Calise *et al* 2020; sea wave energy: Viola *et al* 2016; geothermal energy: Chekir and Hassen 2022). Conversely, water to energy systems included micro-hydropower plants in irrigation network (Pérez-Sánchez *et al* 2016), pumped hydropower storage for wind energy exploitation (Nikolaou *et al* 2020) and water infrastructure to accommodate solar panels (Teotónio *et al* 2020).

### *3.3.2. Water-energy-food*

Agriculture stands out as a major sectorial focus of water-energy-food Nexus assessments in the Mediterranean. A detailed quantification of water and energy consumption in agricultural production was conducted at different scales, from the farm to the irrigation district and river basin scales. When accounting for energy inputs into food production, some studies limited their calculation to the energy required for extracting and distributing water, e.g., de Vito *et al* (2017), Willaarts *et al* (2020), while others extended the quantification to encompass energy consumption associated with machinery, human labour, and production of agricultural inputs (Fabiani *et al* 2020a, Fotia *et al* 2021). Quantifying water and energy need for food production enabled a cross-sectoral evaluation of alternative management practices and interventions, including adopting organic farming (Litskas *et al* 2019), selecting crop patterns (El Gafy *et al* 2017), introducing precision agriculture (Fabiani *et al* 2020b), exploiting alternative water sources (de Vito *et al* 2019) and implementing agro-photovoltaics (Moreda *et al* 2021, Sargentis *et al* 2021). Although all these studies allowed the identification of trade-offs and synergies among crop yield, energy use and water use, their findings were limited to the local scale, failing thus to reveal interlinkages among Nexus sectors at higher organisational levels and beyond agriculture. A more comprehensive overview of the multiple interconnections that exist among activities in the water, energy and food sectors was provided by Mayor *et al* (2015) for the Duero River basin in Spain, while González-Rosell *et al* (2020) integrated water, energy, and food/land modules with economic variables into a unified model to perform a joint analysis of the three economic sectors in Andalusia. To support the governance of water-energy-food Nexus interactions, a number of studies assessed the cross-sectoral impacts resulting from the implementation of policies in a Nexus sector. Examples include subsidising energy for irrigation in Morocco (Doukkali and Lejars 2015), changing water allocation/deallocation rules in Israel (Teitelbaum *et al* 2020) and increasing irrigation water use efficiency in Spain (Willaarts *et al* 2020). Institutions and actor groups can play a role in mediating trade-offs among sectors and in maximising synergies along the supply chains, as illustrated by Villamayor-Tomas *et al* (2015) for the Spanish region of Aragon.

### *3.3.3. Energy-food*

Both energy for food and food for energy interactions are captured by Nexus research in the Mediterranean. On one hand, the use of renewable energy to produce food in rooftop greenhouses (Nadal *et al* 2017) and plant factories (Xydis *et al* 2021), and to guarantee preservation of fresh food in humanitarian context (Aste *et al* 2017) was investigated. On the other hand, Mantziaris *et al* (2017) performed an economic analysis of different energy crops as source of renewable energy for Greece, while Valenti *et al* (2020) demonstrated through a case study in southern Italy that anaerobic digestion of agro-industrial by-products can play a relevant role in renewable energy production.

### *3.3.4. Water-energy-food and climate*

Climate was predominantly added to Nexus analysis as a criterion to evaluate the environmental sustainability of activities and processes within the water, energy and food sectors including: wastewater treatment (Marinelli *et al* 2021), water storage in reservoirs (Aguilera *et al* 2019), food waste management (Laso *et al* 2018), food production (Del Borghi *et al* 2018, Leivas *et al* 2020) and consumption (Tobarra *et al* 2018). Through a more cross-sectorial approach, Ioannou and Laspidou (2022) quantified green-house gases emissions coming from Nexus sectors and integrated them in a system dynamic model to simulate interlinkages and feedback loops in the Greek water-energy-food system and to assess the resilience of the system against external shocks caused by climate change.

Finally, some studies pointed out that policies for climate change adaptation and mitigation could lead to adverse impacts in other sectors. Zografos (2017) highlighted the trade-offs between adapting to climate change, preserving natural ecosystems and sustaining agricultural production in the Ebro River Delta in Spain, while Kati *et al* (2021) warned against the increasing competition over land use between policies on wind energy and biodiversity conservation.

#### *3.3.5. Water-energy-food and ecosystems*

Ecosystems is the least represented component of the WEFE Nexus in the Mediterranean and, similarly to climate, its integration has been mostly limited to assessing the impact of the water, energy, and food sectors on the environment. Through a life cycle analysis approach, a large range of environmental impacts, including eutrophication, ecotoxicity and acidification, were evaluated for activities related to the water, energy, and food supply chains: agro-industrial waste disposals (Valenti *et al* 2020), olive cultivation (Fotia *et al* 2021), biogas production (Pacetti *et al* 2015) and groundwater pumping (Pradeleix *et al* 2015). At the national level, relationships between natural resources, energy production (Rahmane *et al* 2021), and food consumption (Lacirignola *et al* 2014), were investigated through the concept of ecological footprinting. Yet, all these studies fall short in identifying the specific ecosystem within the study area that mutually interacts with the water, energy, and food sectors. With this objective in mind, AbdelHady *et al* (2017) put the Wadi El Rayan Protected Area in Egypt at the centre of a water-energy-food Nexus analysis to quantify trade-offs among ecosystem health, food production and energy production under different water management scenarios. With a stronger emphasis on the benefits derived from ecosystems, Ioannidou *et al* (2022) qualitatively identified the links between water-energy-food Nexus parameters and ecosystems services when assessing potential trade-offs between yield, soil fertility and nutrient cycling in organic orchards, in Cyprus. However, no studies were found that quantified the flows of ecosystem services to the WEF Nexus sectors in the Mediterranean. This lack of evidence may in part explains the finding of Karabulut *et al* (2019), who revealed, through consultation with experts across the Mediterranean, that restoration of ecosystems and their services would theoretically have large benefits across all Nexus sectors, however its implementation is hindered by a lack of awareness among policy makers.

### 3.4. Geographical scale and location of case studies

Figure 5 shows the distribution of the case studies examined in the reviewed literature across the Mediterranean region and represented according to the geographical scale of analysis. Northern Mediterranean countries showed the highest density of Nexus applications both at sub-national scale (i.e., micro, local and river basin) and at national level, with the largest occurrence being in Spain, followed by Greece and Italy. Among the Middle East and North Africa countries, Egypt and Morocco showed the largest implementation of Nexus research with a total of 8 and 5 case studies, respectively. Western Balkan countries, Slovenia, Libya, Syria, and Malta did not contribute with any case study to the reviewed literature. Nexus research in France is also quite limited, with only two case studies at local and river basin scale. It is worth noting that other sub-national scale case studies were identified for Morocco, Egypt, and Spain, but excluded because they do not fall within the defined Mediterranean region.

Interconnections among WEFE Nexus components in the Mediterranean were captured in the reviewed literature at different spatial scales, from the energy saved in household water conservation measures (Barberán *et al* 2019) to the virtual water flows embedded in international food trade (López *et al* 2022). In figure 6 the number of case studies for each geographical scale are reported.

Generally, studies working at micro and local scales focused on quantifying input-output relationships in coupled water, energy, and food production chains, while articles addressing larger scales assessed the implications of these interlinkages in the wider national and international context. As an example, the micro scale adopted by Bertsiou and Baltas (2022) enabled a detailed quantification and optimization of energy use in a desalination plant, but only a study, performed at the national level, could assess the implications of introducing such alternative water sources in meeting national greenhouse gases (GHG) emissions targets (Martin-Gorriz *et al* 2014). Thus, choosing the scale of Nexus analysis requires acknowledging the compromise between the level of analytical detail and the complexity of interactions that can be captured. Few studies attempted to address such shortcomings by working across scales. Examples include the optimization of water and energy supply chains from the technology to

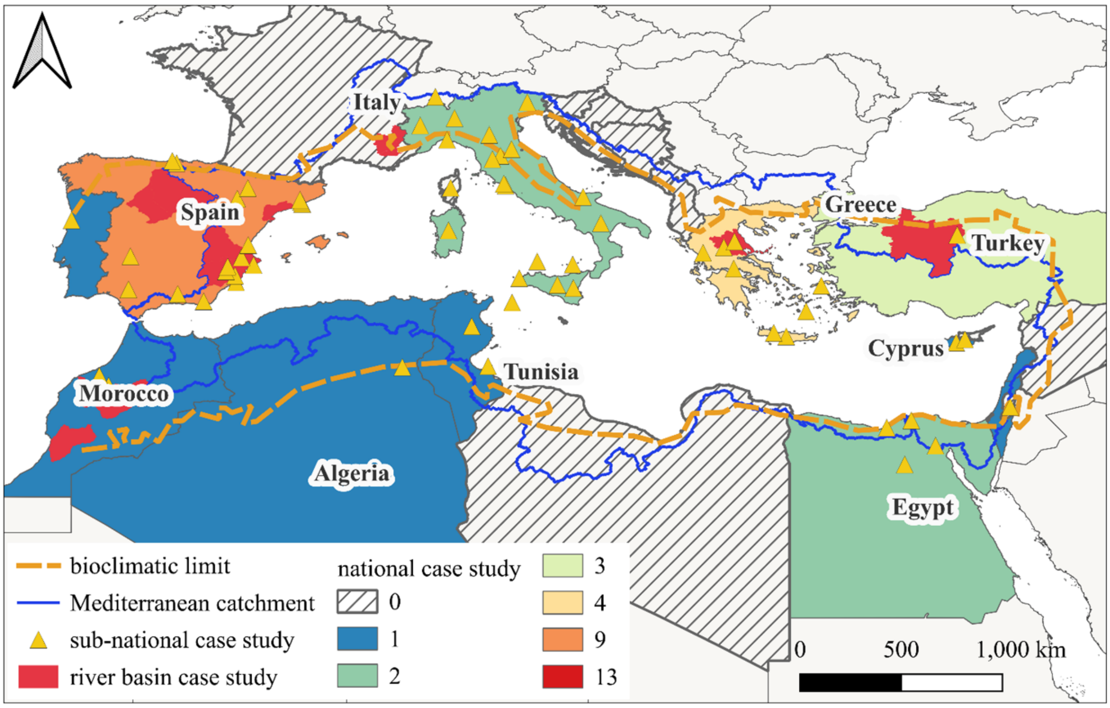


**Figure 5.** Spatial distribution of examined case studies. Sub-national scale case studies (i.e., micro and local) are represented by the yellow triangle, while national case studies are represented by the colour assigned to the country. River basins covered by Nexus assessments are shown in red.

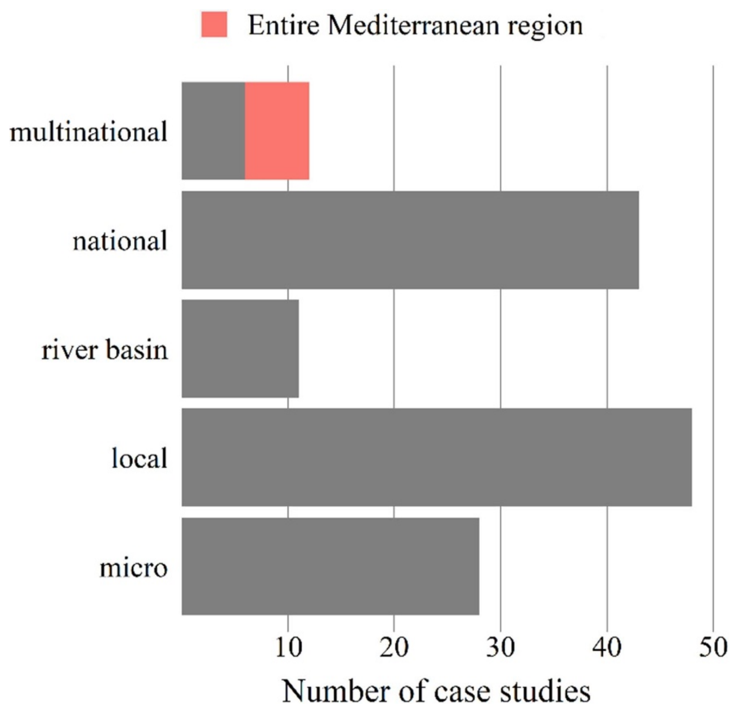


**Figure 6.** Distribution of the reviewed case studies across the different geographical scales.

the national scale (Khan *et al* 2018); the combined analysis of national water use and international virtual water flows to evaluate Egypt's future food gap and water self-sufficiency (Abdelkader *et al* 2018); the integrated modelling of energy systems from technology to the societal organisational level (Di Felice *et al* 2019) and the use of indicators to assess irrigation performance from the farm to the river basin scale (Soto-García *et al* 2013).

Only 6 out of 142 reviewed articles analysed the Mediterranean scale in its entirety. Water and energy footprint of irrigated agriculture was calculated by

Daccache *et al* (2014) for the full Mediterranean region, while Lacirignola *et al* (2014) broadened the analysis to include ecological footprint and to consider food consumption in addition to agricultural production. These early studies highlighted the need of intersectoral policies addressing trade-offs between water use, intensifying food production and reducing the pressures on the scarce resources of the Mediterranean region. Following the delineation of the Agenda 2030, the importance of addressing such water, energy and food interdependencies to coherently achieve the Sustainable Development Goals in all Mediterranean countries was again highlighted by Malagó *et al* (2021) and Saladini *et al* (2018), who proposed indicator-based frameworks to monitor progress towards sustainable development in the Mediterranean.

### 3.5. Approaches and tools for Nexus analysis

Forty-two different methods were employed to study the Nexus in the Mediterranean. Table 3 lists all methods used in the reviewed articles, by grouping them according to the research field they originate from, and by providing examples of their applications in the Mediterranean. The categorization in research fields is based on Albrecht *et al* (2018).

Overall, most of the reviewed articles (75%) used quantitative methods, followed by 9% using qualitative methods alone and 16% using mixed methods. Data analysis and statistical techniques (e.g., cluster analysis and regression analysis) were the most frequently used methods to quantify variables in Nexus sectors and to assess their correlations, therefore providing an important insight into interlinkages among Nexus components (Emir and Karlilar 2022, Sesma-Martín and Puente-Ajovín 2022). Water-related methods were deployed in 20% of the reviewed articles, with a clear preference for water footprint, followed by hydrological modelling and water distribution modelling. Footprinting, more in general, dominated the methodological landscape of Nexus research in the Mediterranean, with nearly 30% of the reviewed articles using at least one among water, energy, carbon and ecological footprints. By linking two sectors in one metric, footprints were employed to quantify resource use along the water, energy, and food supply chains. Similarly, LCA was the most used method from the environmental field to assess the impact of products, processes and activities in Nexus sectors across a wide range of environmental factors, including physical environment and ecosystems. The focus on the water-energy Nexus in the Mediterranean is reflected in a significant use of energy-related methods, mostly targeted to the analysis of coupled water-energy technologies. Few studies, 13%, utilised methods from the field of economics and their use was limited to conducting economic appraisals of technological solutions. Economic methods that instead support the analysis of interactions between economy and the use of natural resources, such as computable general equilibrium model and multiregional input-output model, were barely used by Nexus research in the Mediterranean. The uptake of social science methods for Nexus research in the Mediterranean is relevant. Twenty percent of the reviewed literature deployed at least one social science method to investigate socio-cultural dynamics in governing water, energy, and food sectors, and to account for them in Nexus modelling. Although 40% of the reviewed articles were found to use a combination of methods, integration usually took place across similar disciplines, i.e., energy, environment, water. LCAs offered the largest opportunity for integration, being used with water footprinting for assessing biogas production from energy crops in Italy (Pacetti *et al* 2015) and cultivation of medicinal plants (Litskas *et al* 2019) in Cyprus, and in combination with optimization modelling for identifying solutions that minimise impacts of food processing (Leivas *et al* 2020) and food waste management (Laso *et al* 2018) on natural resources. Integration between natural and social sciences was achieved in the reviewed literature through the use of participatory research techniques (e.g., focus groups, Delphi survey, fuzzy cognitive mapping) to inform the definition and development of system dynamics models simulating the complexity of WEFE Nexus systems (Martinez *et al* 2018, Sušnik *et al* 2018).

Choosing appropriate methods for analysis depends on the type and complexity of Nexus interdependencies being studied and on the geographical scale being addressed. Figure 7 illustrates the scales at which the methods identified in the reviewed literature were applied. At the micro and local scale, LCA, energy modelling and technical-economic analysis tended to prevail, whereas at national level data analysis, statistics and water footprint were more frequently used. Optimization modelling and index/indicators, instead, were more ubiquitous across scale.

### 3.6. Stakeholder engagement

Stakeholders were engaged in 39 studies, 30% of the reviewed articles. Among these, 17 studies approached farmers, local authorities, citizens, and managers of the private sectors to conduct data collection through questionnaires and surveys. In 14 studies, engagement went a step further by co-defining with stakeholders local Nexus challenges and interlinkages among sectors. In-depth semi-structured interviews were conducted to further delineate the local problem and, in some cases, integrated with the construction of casual loop diagrams representing the causes and consequences of the problem from the interviewee's perspective (Halbe *et al* 2015, de Vito *et al* 2019). The highest level of engagement was achieved in 8 studies (out of the total 142 reviewed)

**Table 3.** List of methods used to analyse the Nexus in the reviewed articles. Methods are grouped by research field. The percentage of articles using methods from the listed discipline is provided in parentheses. For each method, representative examples of their application in the reviewed literature are given.

| Method | Number of case studies | Examples of applications in Nexus research in the Mediterranean |
|---|---|---|
| Economics (12%) | | |
| Computable General Equilibrium Model | 1 | Assessing the economic impacts of sectoral and regional competition for water resources under a climate change-driven future scenario (Teotónio *et al* 2020) |
| Technical-Economic Analysis | 11 | Evaluating the technical and economic feasibility of technological solutions, e.g., wind power for plant factories (Xydis *et al* 2021), agrophotovoltaics (Moreda *et al* 2021), integrated renewable energies for wastewater treatment (Odabaş Baş and Aydınalp Köksal 2022) |
| Cost-Benefit Analysis | 1 | Identifying and quantifying private costs and benefits of investments in a technology for improved resource efficiency (Barberán *et al* 2019) |
| Life Cycle Cost Analysis | 1 | Evaluating capital, operating and end-of-use costs of a water-energy Nexus technological solution (Santin *et al* 2020) |
| Multiregional Input-Output Model | 2 | Assessing the impact of international food trade on economy, society and environment (López *et al* 2022) |
| Break-Even Budgeting | 1 | Estimating the critical price of energy crop for its profitable cultivation (Mantziaris *et al* 2017) |
| Energy (14%) | | |
| Energy Model | 10 | Analysing and simulating energy systems for food production (Nadal *et al* 2017), water desalination (Adun *et al* 2022) and irrigation (Salah *et al* 2017); dynamically quantifying interactions between water and energy supply chains at the regional and national level (Fernández-Blanco *et al* 2017, Teotónio *et al* 2020) |
| Energy Indicator (i.e., energy intensity, energy footprint, primary energy demand) | 9 | Computing the energy use associated with activities within Nexus sectors, e.g., irrigation (Daccache *et al* 2014), water supply (Lenzi *et al* 2013), wastewater treatment (Marinelli *et al* 2021), mineral extraction (Lee *et al* 2020) |
| Energy Planning Framework | 1 | Planning interventions for energy production to support electricity and food preservation needs in humanitarian context (Aste *et al* 2017) |
| Environment (20%) | | |
| Life cycle assessment | 14 | Assessing the environmental impact of products, processes, and activities within Nexus sectors: crop cultivation (Fotia *et al* 2021), biogas production (Pacetti *et al* 2015), food waste management (Valenti *et al* 2020), food products (Leivas *et al* 2020), electricity production (Lechón *et al* 2018) and water supply (Arfelli *et al* 2022). Often used to evaluate different management and technological alternatives |
| Carbon Footprint | 11 | Computing the carbon emissions associated with activities within Nexus sectors: crop cultivation (Fotia *et al* 2021), wastewater treatment (Marinelli *et al* 2021), irrigation (Aguilera *et al* 2019) and food consumption (López *et al* 2022). Often used in combination with water footprint and energy indicators |
| Ecological Footprint | 3 | Assessing the environmental impact of food production (Lacirignola *et al* 2014) and energy production (Emir and Karlilar 2022) at the national level |
| Land food footprint | 1 | Analysing the land used to produce food for both organic and conventional agriculture in Tuscany (Lombardi *et al* 2021) |
| Socio-Environmental Accounting | 1 | Accounting of water flows between environment and economy for the analysis of hydropower production (Solera *et al* 2018) |
| Geospatial (6%) | | |
| Spatial Analysis | 6 | Best-siting of technologies and infrastructure to support Nexus resource security: photovoltaic panels on water infrastructure (Kougias *et al* 2016), water harvesting and rooftop agriculture in cities (Zambrano-Prado *et al* 2021), wind farms (Kati *et al* 2021); land suitability analysis for energy crops (Viccaro *et al* 2022) |

(Continued.)

**Table 3.** (Continued.)

| Method | Number of case studies | Examples of applications in Nexus research in the Mediterranean |
|---|---|---|
| Remote Sensing | 2 | Retrieval of input data for hydrological modelling (Psomas *et al* 2016) and spatial planning/analysis (Zambrano-Prado *et al* 2021) |
| Management (4%) | | |
| Decision support systems | 2 | Steering decision making in regulating WEF household consumptions (Teitelbaum *et al* 2020) |
| Multiple-Criteria Decision Analysis | 3 | Assessing the impact of sectoral policies across multiple Nexus targets (Karabulut *et al* 2019). Evaluating different agricultural management practices under a Nexus perspective: deficit irrigation, precision agriculture and reduced fertilization (Psomas *et al* 2021) |
| Indicators (12%) | | |
| Index/Indicators | 17 | Building composite indicators to assess trade-offs and synergies among Nexus targets, e.g., food production, water consumption, energy production and preservation of the environment. Often used to compare different alternatives (de Vito *et al* 2017, El Gafy *et al* 2017, Fabiani *et al* 2020a) |
| Mathematics and Engineering (31%) | | |
| Data and Statistical analysis | 23 | Gathering and compiling data to quantify interlinkages between Nexus components (water-energy-food: Mayor *et al* 2015, water-energy: Ziogou and Zachariadis 2017); various statistical techniques, including trend analysis (Espinosa-Tasón *et al* 2020), forecasting (Melikoglu and Cinel 2020), correlation analysis (Rahmane *et al* 2021), cluster analysis (Ioannidou *et al* 2022), environmental Kuznets curve (Sesma-Martín and Puente-Ajovín 2022) |
| Optimization Model | 13 | Optimizing design and operation of coupled water-energy technologies: desalination (Giudici *et al* 2019, Papapostolou *et al* 2020), pumped hydropower storage (Bertsiou and Baltas 2022); integrated optimization of water and energy supply chains (Khan *et al* 2018); minimizing resource use and environmental impacts in the food supply chain: agriculture (El Gafy *et al* 2017), food processing (Leivas *et al* 2020) and food waste management (Laso *et al* 2018) |
| Engineering Design/Technical Analysis | 6 | Designing water-energy infrastructure: mini-hydropower plant (Comino *et al* 2020) and wave energy converters for desalination (Viola *et al* 2016) |
| Heuristic Technique | 2 | Assessing the intensity of indirect interlinkages among Nexus components (Laspidou *et al* 2019, Papadopoulou and Vlachou 2022) |
| Social Science (20%) | | |
| Institutional Analysis And Development Framework | 2 | Identifying and understanding institutional linkages among Nexus sectors that regulate resource use and supply (Villamayor-Tomas *et al* 2015) |
| Surveys | 6 | Gathering information, mostly through interviews with stakeholders and citizens, on local Nexus challenges (Canessa *et al* 2022), adaptive capacity to resources scarcity (Villamayor-Tomas 2018) and perception and barriers for change (Villar-Navascués *et al* 2020) |
| Participatory Research Techniques | 12 | Co-identification of Nexus interlinkages with stakeholders (González-Rosell *et al* 2020), co-formulation of Nexus problem, vision and potential solutions (Almulla *et al* 2022), co-creation of knowledge and models for Nexus analysis (Sušnik *et al* 2018, Yoon and Saurí 2019). Techniques include workshops (Cremades *et al* 2021), focus group (Canessa *et al* 2022), fuzzy-cognitive mapping (Martinez *et al* 2018) |
| Policy Analysis | 6 | Identifying synergies and trade-offs among sectoral policies (Cremades *et al* 2021) and assessing their coherence under a Nexus perspective (Papadopoulou *et al* 2020) |
| Social Accounting Matrix | 1 | Systematic accounting of activities, commodities and institutions in water, energy, food sectors to determine the economic effects of energy and irrigation subsidies in agriculture (Doukkali and Lejars 2015) |
| Value-chain analysis | 1 | Identify cross-sectorial connections along the water, energy and food supply chains (Villamayor-Tomas *et al* 2015) |

(Continued.)

**Table 3.** (Continued.)

| Method | Number of case studies | Examples of applications in Nexus research in the Mediterranean |
|---|---|---|
| System analysis (12%) | | |
| System Dynamics | 8 | Modelling complex systems of interrelations and feedback among Nexus components (González-Rosell *et al* 2020, Laspidou *et al* 2020); dynamic simulations of a lake's, volume, surface and level to assess water availability (AbdelHady *et al* 2017) |
| Material Flows Analysis | 4 | Quantifying flows and balances of materials and/or energy associated with food trade (Abdelkader *et al* 2018), mineral extraction (Lee *et al* 2020) and integrated waste/wastewater management (Mancini *et al* 2021) |
| Casual Loop Diagram | 3 | Identifying and mapping interlinkages and feedback loops among Nexus components and socio-economic variables (Halbe *et al* 2015, de Vito *et al* 2019) |
| MuSIASEM | 2 | Multi-scale analysis of energy systems in relations to other Nexus components, i.e., water, land use, climate change (Di Felice *et al* 2019) |
| Water (20%) | | |
| Water Footprint | 15 | Computing the water use associated with various activities within Nexus sectors, e.g., food production (Litskas *et al* 2019) food consumption (Zucchinelli *et al* 2021), electricity production (Miglietta *et al* 2018), biogas production (Pacetti *et al* 2015), irrigation (Daccache *et al* 2014), mineral extraction (Lee *et al* 2020) |
| Hydrological Modelling | 6 | Assessing current and/or future water availability for different demands: agriculture (Yaykiran *et al* 2019), hydropower production (Bonato *et al* 2019), thermal plant cooling (Fernández-Blanco *et al* 2017) |
| Water Distribution Modelling | 5 | Evaluating the technical feasibility of micro-hydropower plants (pump as turbine) in irrigation networks (Chacón 2020, Pérez-Sánchez *et al* 2021); simulating water distribution systems to assess energy efficiency (Lenzi *et al* 2013) |
| Computational Fluid Dynamics | 1 | Analysing the performance of a solar distiller for greenhouses (Rabhy *et al* 2019) |
| Hydropower Management Model | 1 | Simulating reservoir operations under climate change and electricity scenarios (Bonato *et al* 2019) |
| Water Resources Management Model (WEAP) | 1 | Representing and simulating various water supplies (surface, groundwater, treated wastewater) and demands (municipal, irrigation) (Almulla *et al* 2022) |
| Crop water modelling | 1 | Calculate crop water requirements to evaluate water and energy savings through irrigation planning (Brik *et al* 2022) |
| Other (1%) | | |
| Laboratory Experiment | 1 | Testing the application of fertilizer drawn forward osmosis (Amin *et al* 2021) |
| Water-energy audit | 1 | Quantifying water flows and energy consumption in a building to assess the impact of implementing water efficiency measures (Rodrigues *et al* 2020) |

by including stakeholders in the co-creation of methods of analysis and in the co-development of solutions. González-Rosell *et al* (2020) built on the results of a fuzzy cognitive mapping performed with stakeholders in Andalusia to create a model of interconnected water, energy and food sectors that was subsequently validated and tested by the same stakeholders through an iterative process. A constant flow of communication among researchers and stakeholders, and their regular consultation throughout the research project, were central to the co-development of a serious game to explore the water-energy-food-land-climate Nexus in Sardinia (Sušnik *et al* 2018) and to the co-creation of Nexus decision metrics for managing the agriculture-water-energy Nexus in the Souss-Mass basin (Almulla *et al* 2022).

### 3.7. Nexus research operationalization

The classification of the reviewed articles against the criteria revealed a clustering of Nexus research in the Mediterranean around two main contexts of operationalization, defined in this review as 'natural resources management' and 'sustainable technology'. The natural resources management group gathers articles that employ Nexus thinking to advance knowledge on the interconnectedness of water, energy and food sectors and their relationships with society and

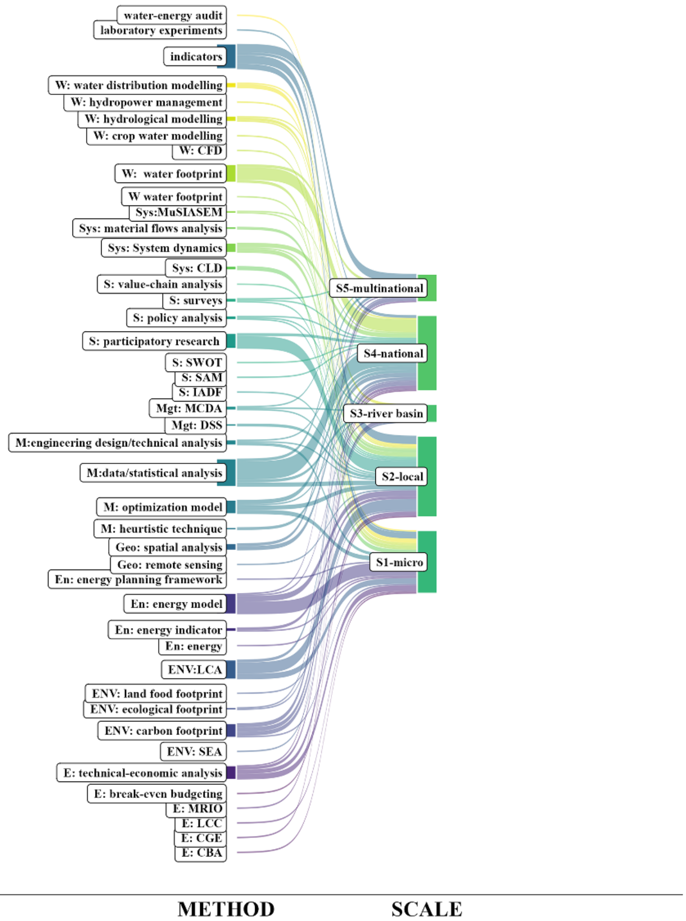


**Figure 7.** Methods used for Nexus assessments at different geographical scales. The first letters in the method's name indicate the method's discipline. W: water; Sys: system analysis, S: social science, Mgt: management, M: mathematics and engineering, Geo: geospatial, En: energy, ENV: environment, E: economics.

economy, while the sustainable technology cluster encompasses articles that examine the implementation of specific technological solutions to support the efficient use of Nexus resources. Figure 8 shows the relative contribution of the two clusters to the reviewed literature and their predominant attributes for each classification criteria. The sustainable technology group is dominated by research on the Nexus between two components, mostly water-energy Nexus and energy-food Nexus, and it focuses on technological systems, such as renewable energies for desalination, hydraulic pump reservoirs for energy storage, agricultural waste for bioenergy production and micro hydropower plants in irrigation networks. These studies aimed at supporting the implementation of technologies by assessing their best siting and feasibility, and by optimising their design and operations. Technical-economic analysis was often used in the planning stage to assess their feasibility alongside the use of LCA for assessing their environmental impact, whereas optimization techniques and detailed water or energy modelling were deployed to inform their design. The operationalization of the Nexus approach in the context of natural resources management is mostly characterized by studies addressing Nexus combinations of three or more components, i.e. water-energy-food, WEFE and water-energy-food-climate. These studies deployed a wide range of quantitative and qualitative methods at different spatial scales to understand the complexity of the resource system, to quantify the relationships among Nexus sectors and to assess future scenarios for adequate policy responses and good governance.

Although the reviewed literature offered a rather sharp delineation of the two contexts in which Nexus research in the Mediterranean has been operationalized, few articles were found to be placed at the interface between the natural resources management and sustainable technology groups. In most cases, such articles evaluated constraints and benefits of adopting a type of technological or infrastructural intervention in terms of natural resources availability and security at the local or national scale. Mancini *et al* (2021) assessed the advantages of implementing an integrated wastewater, solid waste and energy generation system in a metropolitan area of southern Italy to increase circularity in the use of resources, to support local energy needs and to reduce emissions. For a neighbourhood in Barcelona,

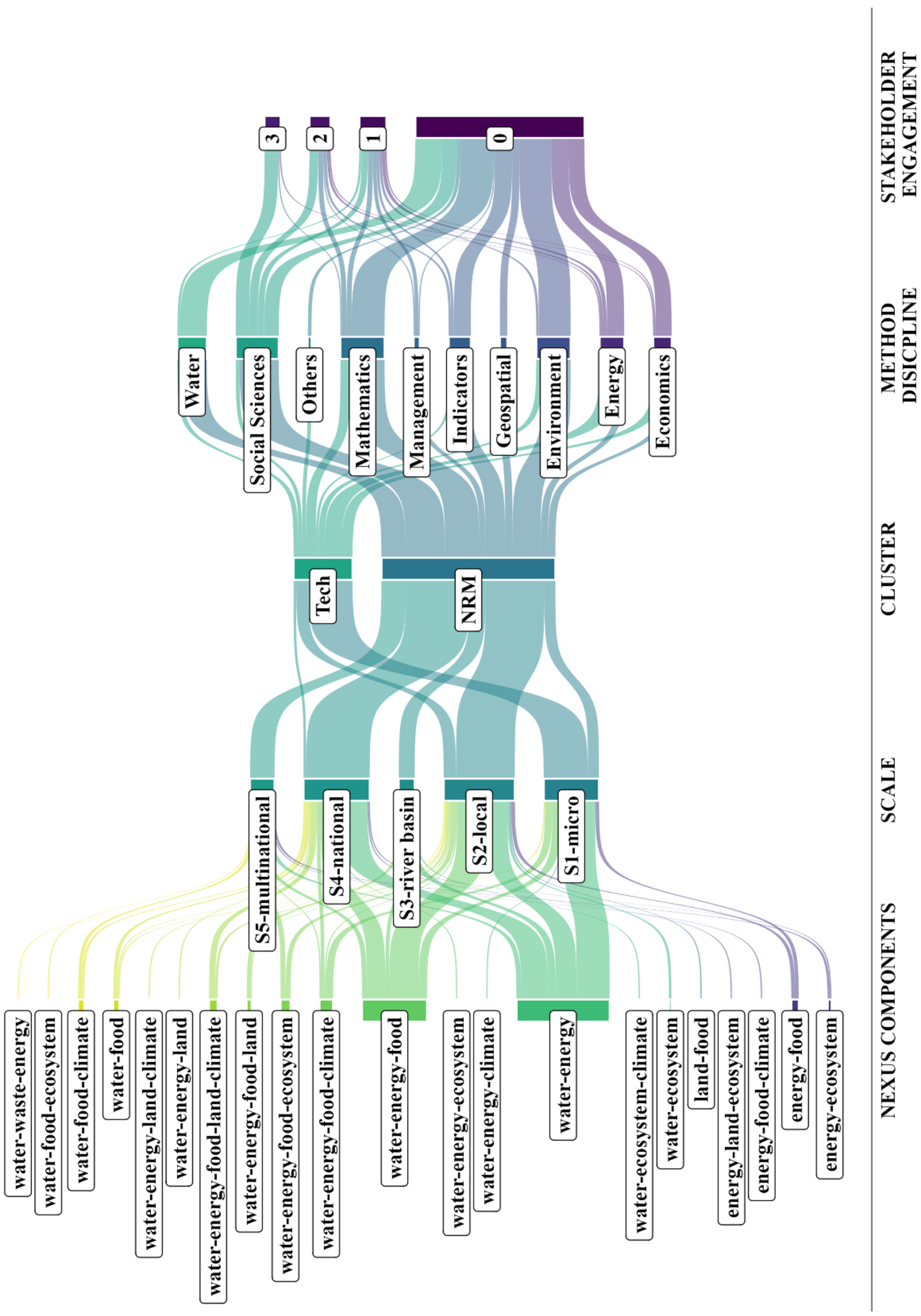


**Figure 8.** The distribution of the reviewed case studies between the natural resources management (NRM) and sustainable technology (Tech) clusters and across the classification criteria.

Toboso-Chavero *et al* (2019) analysed the technical feasibility and environmental implications of introducing urban agriculture, rainwater harvesting and photovoltaics panels on roofs of residential buildings to meet the local water, energy, food demands, optimise land use and reduce emissions. The aim of such studies was therefore not to design specific technologies but rather to assess their contribution to a sustainable use of natural resources.

## 4. Discussion

### 4.1. From water-energy-food to water-energy and WEFE Nexus

The strong focus on the water-energy Nexus is a key trait of the Mediterranean region that has not been reported in previous evaluations of Nexus research at the global scale (Fernandes Torres *et al* 2019) or regionally (Bian and Liu 2021). While Botai *et al* (2021) shows that for Africa, food security is central to Nexus research and that water resources are seen as one of the enabling factors to achieve such security, in the Mediterranean region the attention is placed on ensuring availability of water for domestic and irrigation purposes, and on its dependency on energy use. In fact, to cope with water scarcity Mediterranean countries need to tap into energy-intensive water resources, while maintaining water and energy services affordable. At the same time, the scope of Nexus assessment has expanded to additional components, with land being the first one to be added, followed by climate and ecosystems. Yet, in the Mediterranean, the integration of ecosystems and climate to the WEF Nexus was shown to be only partial and predominantly focused on assessing unilateral impact relationships, rather than identifying the mutual interlinkages and feedback dynamics. Thus, we call for new studies that comprehensively analyse the impacts on Mediterranean ecosystems originated from the water, energy and food resource sectors and assess how these impacts may inhibit the capacity of ecosystems to provide services to the same sectors. These studies shall account for the intrinsic interlinkages between climate and ecosystems, which are likely to amplify the risks posed to the water, energy, and food security of the region, through the consequences of climate-driven issues such as wildfires, spread of non-native species, water pollution and biodiversity loss (Doblas-Miranda *et al* 2017). The WEFE-climate Nexus therefore represents a promising research perspective to untangle and explore interconnected risks for ecosystems and society of the Mediterranean. To this end, the First Mediterranean Assessment Report by the Mediterranean Experts on Environmental and Climate Change represents a strong reference for any Nexus studies in the region, since it provides a comprehensive synthesis of knowledge on the major drivers of change and impacts across resource systems (MedECC 2020).

### 4.2. Multidimensionality of Nexus research

Nexus research in the Mediterranean has also evolved in terms of dimensions being investigated. Interlinkages among water, energy and food were not only assessed from a biophysical modelling perspective but have also been considered under socio-economic and governance dimensions. Such a need for Nexus research has been extensively pointed out, but not fully addressed yet (Galaitsi *et al* 2018, van Gevelt 2020). The reviewed literature contributes to the debate by offering insights on how economic instruments (e.g., energy market, water pricing, subsidies) can influence trends in Nexus interlinkages and on how different social groups relate to the local WEF Nexus systems. In particular, the social security of local communities may be compromised by trade-offs arising among the Nexus sectors, (Zografos 2017, Yoon *et al* 2018), while, at the same time, citizens affect the development of WEF systems through their consumption patterns (Lombardi *et al* 2021). The consideration of the societal dimension is also manifested by the inclusion of sectorial perspectives expressed by local stakeholders in the co-definition of Nexus issues, knowledge, and solutions. Such an attitude to the science-stakeholder interface, defined by Alamanos *et al* (2022) as a 'System Innovation Approach', supports the achievement of a coordinated and socially acceptable management of natural resources (Sušnik *et al* 2021), helps improving the governance impacts of Nexus assessment and, we argue, shall be extended to those applications of Nexus research that to date have seen less stakeholder involvement. This is the case for the reviewed articles operationalizing Nexus research in the context of sustainable technologies. The involvement of stakeholders and users in assessing the needs for specific technologies and in evaluating their local socio-economic feasibility shall become more prominent in Nexus research and could build upon the methodological frameworks presented by Aste *et al* (2017) for energy-food technology planning in humanitarian context and by Emec *et al* (2015) for designing production systems with hybrid water and energy generation. Overall, the governance, socio-economic and biophysical dimensions of the Nexus were often investigated separately, with only few studies trying to holistically analyse Nexus interactions across these dimensions. Considering the role of institutions, stakeholders and citizen in shaping WEF Nexus systems in combination with a bio-physical assessment of WEF Nexus resources and an analysis of economic dynamics, would provide a comprehensive overview of Nexus systems for evidence-based decision-making (Akinsete *et al* 2022).

### 4.3. Variety of methods and scales of analysis

A multidimensional examination of Nexus interlinkages implies embracing multidisciplinary, gathering data from different scientific fields and it calls for an integration of methods and geographical scales, an aspect that was rarely found in the reviewed literature. In fact, the methodological landscape emerging from the reviewed literature is faced by a disparity of discipline-focused methods with few being recurrently deployed: data analysis and statistics, footprint, index/indicators, LCA and optimisation modelling. At the global level, Albrecht *et al* (2018) provides a comprehensive synthesis of methods for Nexus assessments. Although their results cannot be directly compared to our findings, since they disregarded Nexus types of two components from the analysis (e.g., water-energy, water-food), some observations can be made. Firstly, while economic methods are significantly used for Nexus assessments globally, their deployment in the Mediterranean is very limited, especially at the national and international scale. This results in a lack of quantified evidence on how economic factors and policies impact Nexus systems and how the WEF Nexus influences the economic growth in the Mediterranean region. Economic assessments of Nexus systems are therefore needed to support what Markantonis *et al* (2019) highlight as a key recommendation for Nexus operationalization in the region, i.e., implementing water pricing and other economic instruments. Secondly, and in contrast with Albrecht *et al* (2018), we found that a relevant number of studies used data and statistical analysis as their main method to explore the interactions between Nexus sectors. Although they represent a first step in understanding, quantifying and correlating resource consumption in water, energy and food supply chains, their ability to inform policy making remains limited (Zhang *et al* 2018). Lastly, energy-related methods are more frequently used in the Mediterranean then at the global scale, mostly driven by the regional interest on the water-energy interdependencies.

The departmental work throughout the different scales often ignored exogenous variables and drivers, resulting in 'isolated spaces' studies. For example, LCA-based assessments mainly focused on micro (farm or industry) and local scales, providing a strong numerical output, but ignoring the Mediterranean and contextual setting. Hence, new studies addressing the entire Mediterranean region, which were rare in our review, could provide a common background to connect these "isolated spaces". We recommend building on existing methodologies and expand them to larger geographical scale without developing specific methods or theories. For instance, a two-component water-energy study in a specific country can be expanded to the Mediterranean basin by considering energy imports/exports, transboundary condition, and ecological constraints. The large divide in frequency of Nexus case studies among Mediterranean countries observed in this review calls for increased cooperation among researchers and highlights the need of proving the benefits of the Nexus approach in those countries to date not yet covered by demonstration sites, particularly the Western Balkan countries surrounding the Mediterranean Sea. In doing so, however, it is important to recognise and harness the plurality of knowledge, perspectives and challenges present across the Mediterranean region to more holistically and equitably advance Nexus implementation, avoiding therefore a large divide between places of Nexus research production and its operationalization (Wiegleb and Bruns 2018).

### 4.4. Applications of Nexus research

The reviewed articles highlight sustainable technology as a key field of Nexus operationalization. Integrated technologies in the water, energy and food supply chains are crucial for simultaneously achieving water, energy, food security, and promoting resource use efficiency. Such technologies are also helping to mainstream the Nexus approach as they constitute tangible demonstrators of the benefits gained by adopting a multi-sectoral thinking. Yet, to date, the Nexus has mostly provided a perspective under which the role of existing and emerging technologies in achieving sustainable development can be further promoted, rather than it being the initiator of new technological solutions. For example, the use of renewable energies for desalination, now often referred to as Nexus technology, has been widely studied even before the conceptualization of the WEF security Nexus. This may change in the future with international initiatives such as the Water and Energy for Food Grand Challenge[9], which harness the interdependencies among these sectors to stimulate the development and upscaling of technological innovation. However, Hoff *et al* (2019) argue, through a review of 4 project case studies in the Mediterranean, that for a successful implementation of technological advancements, these need to be framed in a policy and regulatory environment so that synergies are maximised and potential negative consequences for the environment and society are controlled. We expand by affirming that to do so, technology-oriented studies under a Nexus perspective should go beyond pure engineering and modelling exercise, which is the case for the majority of the reviewed articles, and provide a systematic evaluation of synergies and trade-offs across sectors and scales. We therefore call for further Nexus studies that harmonize research objectives and methodologies from the field of natural resources management and sustainable technologies, to provide policy makers with actionable information for a coherent achievement of sustainable development.

[9] https://we4f.org/who-we-are.

## 5. Conclusions

A novel literature review was presented investigating the status-quo of the WEFE Nexus scholarship, in terms of academic research outputs supporting the operationalization of the WEFE Nexus in the Mediterranean. The large variety of reviewed topics, methods and applications indicates a lack of harmony in the 'ideas', 'relationships' and 'practices' associated with the Nexus. On the other hand, this expected heterogeneity unveils the potential for Nexus thinking to becoming a leading transdisciplinary framework to address the diverse pillars of sustainability. Moreover, by focusing on the interlinkages between resources rather than on the resources themselves, the Nexus approach demonstrates its applicability across different research fields and questions, whether concerning the management of natural resource, or the development of innovative technological solutions. Such a holistic and transversal perspective therefore offers an opportunity for the Mediterranean region to coherently mitigate nuisance effects of climate extremes and natural disasters and adapting to future climate and environmental changes, while accelerating progress towards the achievement of the Sustainable Development Goals. However, our review reveals that current research still falls short in providing multifaceted and integrative Nexus assessments. Thus, in summarizing outcomes of the presented WEFE Nexus review, we highlight future directions for the Nexus research community in the Mediterranean, that might catalyse further advancements:

1- The level of knowledge and research operationalization reached in the water-energy Nexus, first, and, to a less extent, in the water-energy-food Nexus, shall be firmly pursued in more complex systems. Within the WEF Nexus, more evidence is needed on the energy-to-food and food-to-water interlinkages, prompting additional data collection and analysis. Further research is also needed in the identification and quantification of the mutual relationships between climate, ecosystems and the WEF systems.
2- The assimilation of socio-economic variables and processes in biophysical-driven Nexus assessment shall be further promoted to account for external drivers determining resources use and for understanding the socio-economic impacts of actions taken in WEFE Nexus sectors. This would also help in making findings of Nexus research more relevant to governance.
3- The Mediterranean scale should receive further attention. Besides having biophysical similarities and sharing common risks associated with climate and environmental change, Mediterranean countries also represent a unique socio-economic region, where interconnected societal and biophysical spheres are impacted by a variety of administrative, historical, and cultural barriers. WEFE Nexus assessments performed at the scale of the Mediterranean region could therefore help identify hotspots in the use of water, energy and food resources, their drivers, and it would provide a strong regional background for the implementation of local Nexus solutions.

Our proposed research gaps aim at providing a pathway to develop the representation of such complex systems and allowing the dissemination of the Nexus approach, while increasing its validity and significance across multiple geographic and socio-economic scales.

## Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

## Acknowledgments

We are sincerely thankful to the anonymous reviewers, who contributed to improving the quality of our work through their insightful and constructive comments.

## Funding

Authors gratefully acknowledge the financial support of the NEXUS-NESS project that has received funding from the PRIMA Programme, an Art. 185 initiative supported and funded under Horizon 2020, the European Union's Framework Programme for Research 65 and Innovation, with Grant Agreement No. 2042 (https://prima-nexus-ness.org/) as well as the 'PON Ricerca e Innovazione 2014-2020: Istruzione e ricerca per il recupero—REACT-EU' Programme of the Italian Government, through the PhD scholarship Granted to Enrico Lucca (scholarship n. DOT137M5SZ n. 2, 2022–2024).

## Conflict of interest

The authors declare no conflict of interest.

## Authors contribution

Enrico Lucca: Conceptualization; Methodology; Investigation; Data Curation; Visualization; Writing—Original Draft. Jérôme El Jeitany: Conceptualization; Methodology; Investigation; Data Curation; Visualization; Software; Writing—Original Draft. Giulio Castelli: Conceptualization; Methodology; Writing—Review & Editing; Funding acquisition. Tommaso Pacetti: Conceptualization; Methodology; Writing—Review & Editing; Funding acquisition. Elena Bresci: Conceptualization;

Methodology; Writing—Review & Editing; Supervision; Funding acquisition. Fernando Nardi: Writing—Review & Editing; Funding acquisition. Enrica Caporali: Conceptualization; Methodology; Writing—Review & Editing; Supervision; Funding acquisition.

## ORCID iDs

Enrico Lucca https://orcid.org/0000-0001-5287-6301
Jerome El Jeitany https://orcid.org/0000-0003-1988-0565
Giulio Castelli https://orcid.org/0000-0002-0209-0869

## References

AbdelHady R S, Fahmy H S and Pacini N 2017 Valuing of Wadi El-Rayan ecosystem through water–food–energy Nexus approach *Ecohydrol. Hydrobiol.* **17** 247–53

Abdelkader A, Elshorbagy A, Tuninetti M, Laio F, Ridolfi L, Fahmy H and Hoekstra A Y 2018 National water, food, and trade modeling framework: the case of Egypt *Sci. Total Environ.* **639** 485–96

Adun H, Ishaku H P and Ogungbemi A T 2022 Towards renewable energy targets for the middle East and North African region: a decarbonization assessment of energy-water Nexus *J. Clean. Prod.* **374** 133944

Aguilera E, Vila-Traver J, Deemer B R, Infante-Amate J, Guzmán G I and González de Molina M 2019 Methane emissions from artificial waterbodies dominate the carbon footprint of irrigation: a study of transitions in the food–energy–water–climate Nexus (Spain, 1900–2014) *Environ. Sci. Technol.* **53** 5091–101

Akinsete E, Koundouri P, Kartala X, Englezos N, Lautze J, Yihdego Z, Gibson J, Scholz G, van Bers C and Sodoge J 2022 Sustainable WEF Nexus management: a conceptual framework to integrate models of social, economic, policy, and institutional developments *Front. Water* **4** 727772

Alamanos A, Koundouri P, Papadaki L and Pliakou T 2022 A system innovation approach for science-stakeholder interface: theory and application to water-land-food-energy Nexus *Front. Water* **3** 744773

Albrecht T R, Crootof A and Scott C A 2018 The water-energy-food Nexus: a systematic review of methods for Nexus assessment *Environ. Res. Lett.* **13** 043002

Almulla Y, Ramirez C, Joyce B, Huber-Lee A and Fuso-Nerini F 2022 From participatory process to robust decision-making: an agriculture-water-energy Nexus analysis for the Souss-Massa basin in Morocco *Energy Sustain. Dev.* **70** 314–38

Amin G, Nasr P and Sewilam H 2021 An experimental study on draw solution performance in fertilizer drawn forward osmosis under water energy food Nexus framework in Egypt *Desalin. Water Treat.* **210** 70–80

Arfelli F, Ciacci L, Vassura I and Passarini F 2022 Nexus analysis and life cycle assessment of regional water supply systems: a case study from Italy *Resour. Conserv. Recycl.* **185** 106446

Aste N, Barbieri J, Berizzi A, Colombo E, Del Pero C, Leonforte F, Merlo M and Riva F 2017 Innovative energy solutions for improving food preservation in humanitarian contexts: a case study from informal refugees settlements in Lebanon *Sustain. Energy Technol. Assess.* **22** 177–87

Barberán R, Colás D and Egea P 2019 Water supply and energy in residential buildings: potential savings and financial profitability *Sustainability* **11** 295

Bauen A, O'Connor D, Edwards R, Fabiosa J, Laborde D, Malins C, Overmars K and Plevin R 2015 The land use change impact of biofuels consumed in the EU: quantification of area and greenhouse gas impacts. (BIENL13120) (Ecofys) (available at: http://pure.iiasa.ac.at/id/eprint/12310/) (Accessed 05 February 2019)

Bazilian M *et al* 2011 Considering the energy, water and food Nexus: towards an integrated modelling approach *Energy Policy* **39** 7896–906

Bazzana D, Comincioli N, El Khoury C, Nardi F and Vergalli S 2023 WEF Nexus policy review of four Mediterranean countries *MDPI Land* **12** 473

Bertsiou M M and Baltas E 2022 Management of energy and water resources by minimizing the rejected renewable energy *Sustain. Energy Technol. Assess.* **52** 102002

Bian Z and Liu D 2021 A comprehensive review on types, methods and different regions related to water–energy–food Nexus *Int. J. Environ. Res. Public Health* **18** 8276

Bonato M, Ranzani A, Patro E R, Gaudard L and De Michele C 2019 Water-energy Nexus for an Italian storage hydropower plant under multiple drivers *Water* **11** 1838

Botai J O *et al* 2021 A review of the water–energy–food Nexus research in Africa *Sustainability* **13** 1762

Branche E 2017 The multipurpose water uses of hydropower reservoir: the SHARE concept *C. R. Physique* **18** 469–78

Brik M, Guerrah A and Atia A 2022 Water-energy Nexus: a systematic analysis and evaluation of a center-pivot irrigation system. Energy sources part recovery util *Environ. Eff.* **44** 8299–313

Calise F, Cappiello F L, Vicidomini M and Petrakopoulou-Robinson F 2020 Water-energy Nexus: a thermoeconomic analysis of polygeneration systems for small Mediterranean islands *Energy Convers. Manage.* **220** 113043

Canessa C, Vavvos A, Triliva S, Kafkalas I, Vrachioli M and Sauer J 2022 Implementing a combined Delphi and Focus Group qualitative methodology in Nexus research designs-the case of the WEFE Nexus in Apokoronas, Crete *PLoS One* **17** e0271443

Carmona-Moreno C, Crestaz E, Cimmarrusti Y, Farinosi F, Biedler M, Amani A, Mishra A and Carmona-Gutierrez A (eds) 2021 *Implementing the Water–Energy–Food–Ecosystems Nexus and Achieving the Sustainable Development Goals* (United Nations Educational, Scientific and Cultural Organization (UNESCO); European Commission, Joint Research Centre, Institute on Sustainable Resources, Water and Marine Resources Unit; IWA Publishing)

Chacón M C, Rodríguez Díaz J A, Morillo J G and Mc Nabola A 2020 Hydropower energy recovery in irrigation networks: validation of a methodology for flow prediction and pump as turbine selection *Renew. Energy* **147** 1728–38

Chekir N and Hassen D 2022 Tunisian geothermal potential for desalination *Water-Energy-Nexus in the Ecological Transition, Advances in Science* ed V Naddeo, K-H Choo and M Ksibi (Springer) pp 237–40

Comino E, Dominici L, Ambrogio F and Rosso M 2020 Mini-hydro power plant for the improvement of urban water-energy Nexus toward sustainability—a case study *J. Clean. Prod.* **249** 119416

Cramer W *et al* 2018 Climate change and interconnected risks to sustainable development in the Mediterranean *Nat. Clim. Change* **8** 972–80

Cremades R, Sanchez-Plaza A, Hewitt R J, Mitter H, Baggio J A, Olazabal M, Broekman A, Kropf B and Tudose N C 2021 Guiding cities under increased droughts: the limits to sustainable urban futures *Ecol. Econ.* **189** 107140

Daccache A, Ciurana J S, Rodriguez Diaz J A and Knox J W 2014 Water and energy footprint of irrigated agriculture in the Mediterranean region *Environ. Res. Lett.* **9** 124014

de Vito R, Pagano A, Portoghese I, Giordano R, Vurro M and Fratino U 2019 Integrated approach for supporting sustainable water resources management of irrigation based on the WEFN framework *Water Resour. Manage.* **33** 1281–95 de Vito R, Portoghese I, Pagano A, Fratino U and Vurro M 2017 An index-based approach for the sustainability assessment of irrigation practice based on the water-energy-food Nexus framework *Adv. Water Resour.* **110** 423–36

Del Borghi A, Strazza C, Magrassi F, Taramasso A C and Gallo M 2018 Life cycle assessment for eco-design of product–package systems in the food industry—the case of legumes *Sustain. Prod. Consum.* **13** 24–36

Di Felice L J, Ripa M and Giampietro M 2019 An alternative to market-oriented energy models: Nexus patterns across hierarchical levels *Energy Policy* **126** 431–43

Doblas-Miranda E *et al* 2017 A review of the combination among global change factors in forests, shrublands and pastures of the Mediterranean Region: beyond drought effects *Glob. Planet. Change* **148** 42–54

Doukkali M R and Lejars C 2015 Energy cost of irrigation policy in Morocco: a social accounting matrix assessment *Int. J. Water Resour. Dev.* **31** 422–35

El Gafy I, Grigg N and Reagan W 2017 Water-food-energy Nexus index to maximize the economic water and energy productivity in an optimal cropping pattern *Water Int.* **42** 495–503

Elsayed H, Djordjevic S, Savic D, Tsoukalas I and Makropoulos C 2022 Water-food-energy Nexus for transboundary cooperation in Eastern Africa *Water Supply* **22** 3567–87

Eltawil M A, Zhengming Z and Yuan L 2009 A review of renewable energy technologies integrated with desalination systems *Renew. Sustain. Energy Rev.* **13** 2245–62

Emec S, Bilge P and Seliger G 2015 Design of production systems with hybrid energy and water generation for sustainable value creation *Clean Technol. Environ. Policy* **17** 1807–29

Emir F and Karlilar S 2022 Application of RALS cointegration test assessing the role of natural resources and hydropower energy on ecological footprint in emerging economy *Energy Environ.* **34** 0958305X2110738

Espinosa-Tasón J, Berbel J and Gutiérrez-Martín C 2020 Energized water: evolution of water-energy Nexus in the Spanish irrigated agriculture, 1950–2017 *Agric. Water Manage.* **233** 106073

Fabiani S, Vanino S, Napoli R and Nino P 2020a 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

Fabiani S, Vanino S, Napoli R, Zajíček A, Duffková R, Evangelou E and Nino P 2020b Assessment of the economic and environmental sustainability of variable rate technology (VRT) application in different wheat intensive European agricultural areas. A water energy food Nexus approach *Environ. Sci. Policy* **114** 366–76

Fernandes Torres C J, Peixoto de Lima C H, Suzart de Almeida Goodwin B, Rebello de Aguiar Junior T, Sousa Fontes A, Veras Ribeiro D, Saldanha Xavier da Silva R and Dantas Pinto Medeiros Y 2019 A literature review to propose a systematic procedure to develop “Nexus thinking” considering the water–energy–food Nexus *Sustainability* **11** 7205

Fernández-Blanco R, Kavvadias K and Hidalgo González I 2017 Quantifying the water-power linkage on hydrothermal power systems: a Greek case study *Appl. Energy* **203** 240–53

Florin M and Gabriel E 1991 Integrated resource management: the answer to a socio-economic problem *GeoJournal* **25** 109–13

Fotia K, Mehmeti A, Tsirogiannis I, Nanos G, Mamolos A P, Malamos N, Barouchas P and Todorovic M 2021 LCA-based environmental performance of olive cultivation in Northwestern Greece: from rainfed to irrigated through conventional and smart crop management practices *Water* **13** 1954

Galaitsi S, Veysey J and Huber-Lee A, 2018 Where is the added value? A review of the water-energy-food Nexus literature *SEI Working paper* (Stockholm Environment Institute)

Giudici F, Castelletti A, Garofalo E, Giuliani M and Maier H R 2019 Dynamic, multi-objective optimal design and operation of water-energy systems for small, off-grid islands *Appl. Energy* **250** 605–16

González-Rosell A, Blanco M and Arfa I 2020 Integrating stakeholder views and system dynamics to assess the water–energy–food Nexus in Andalusia *Water* **12** 3172

Halbe J, Pahl-Wostl C, Lange M A and Velonis C 2015 Governance of transitions towards sustainable development—the water–energy–food Nexus in Cyprus *Water Int.* **40** 877–94

Hoff H, 2011 Understanding the Nexus. Background paper for the Bonn2011 conference: the water, energy and food security Nexus in: environmental research letters (Stockholm Environment Institute)

Hoff H *et al* 2019 A Nexus approach for the MENA region—from concept to knowledge to action *Front. Environ. Sci.* **7** 48

Hoolohan C *et al* 2018 Engaging stakeholders in research to address water–energy–food (WEF) Nexus challenges *Sustain. Sci.* **13** 1415–26

Hülsmann S, Sušnik J, Rinke K, Langan S, van Wijk D, Janssen A B and Mooij W M 2019 Integrated modelling and management of water resources: the ecosystem perspective on the Nexus approach *Curr. Opin. Environ. Sustain.* **40** 14–20

Ioannidou S, Litskas V, Stavrinides M and Vogiatzakis I N 2022 Placing ecosystem services within the water–food–energy–climate Nexus: a case study in Mediterranean mixed orchards *Agronomy* **12** 2224

Ioannou A E and Laspidou C S 2022 Resilience analysis framework for a water–energy–food Nexus system under climate change *Front. Environ. Sci.* **10** 820125

Karabulut A A, Udias A and Vigiak O 2019 Assessing the policy scenarios for the ecosystem water food energy (EWFE) Nexus in the Mediterranean region *Ecosyst. Serv.* **35** 231–40

Kati V, Kassara C, Vrontisi Z and Moustakas A 2021 The biodiversity-wind energy-land use Nexus in a global biodiversity hotspot *Sci. Total Environ.* **768** 144471

Khan Z, Linares P, Rutten M, Parkinson S, Johnson N and García-González J 2018 Spatial and temporal synchronization of water and energy systems: towards a single integrated optimization model for long-term resource planning *Appl. Energy* **210** 499–517

Kougias I, Bódis K, Jäger-Waldau A, Moner-Girona M, Monforti-Ferrario F, Ossenbrink H and Szabó S 2016 The potential of water infrastructure to accommodate solar PV systems in Mediterranean islands *Sol. Energy* **136** 174–82

Lacirignola C, Capone R, Debs P, El Bilali H and Bottalico F 2014 Natural resources â€“ food Nexus: food-related environmental footprints in the Mediterranean countries *Front. Nutrition* **1** 1–16

Laso J *et al* 2018 Combined application of life cycle assessment and linear programming to evaluate food waste-to-food strategies: seeking for answers in the Nexus approach *Waste Manage.* **80** 186–97

Laspidou C S, Mellios N K and Kofinas D T 2019 Towards ranking the water-energy-food-land use-climate Nexus interlinkages for building a Nexus conceptual model with a heuristic algorithm *Water* **11** 306

Laspidou C S, Mellios N K, Spyropoulou A E, Kofinas D T and Papadopoulou M P 2020 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

Lechón Y, De La Rúa C and Cabal H 2018 Impacts of decarbonisation on the water-energy-land (WEL) Nexus: a case study of the Spanish electricity sector *Energies* **11** 1203

Lee S-H, Assi A T, Daher B, Mengoub F E and Mohtar R H 2020 A water-energy-food Nexus approach for conducting trade-off analysis: Morocco’s phosphate industry in the Khouribga region *Hydrol. Earth Syst. Sci.* **24** 4727–41

Leivas R, Laso J, Abejón R, Margallo M and Aldaco R 2020 Environmental assessment of food and beverage under a NEXUS water-energy-climate approach: application to the spirit drinks *Sci. Total Environ.* **720** 137576

Lenzi C, Bragalli C, Bolognesi A and Artina S 2013 From energy balance to energy efficiency indicators including water losses *Water Sci. Technol. Water Supply* **13** 889–95

Lionello P and Scarascia L 2018 The relation between climate change in the Mediterranean region and global warming *Reg. Environ. Change* **18** 1481–93

Litskas V, Chrysargyris A, Stavrinides M and Tzortzakis N 2019 Water-energy-food Nexus: a case study on medicinal and aromatic plants *J. Clean. Prod.* **233** 1334–43

Lombardi G V, Parrini S, Atzori R, Stefani G, Romano D, Gastaldi M and Liu G 2021 Sustainable agriculture, food security and diet diversity. The case study of Tuscany, Italy *Ecol. Model.* **458** 109702

López L-A, Tobarra M-A, Cadarso M-Á, Gómez N and Cazcarro I 2022 Eating local and in-season fruits and vegetables: carbon-water-employment trade-offs and synergies *Ecol. Econ.* **192** 107270

Malagó A, Comero S, Bouraoui F, Kazezyılmaz-Alhan C M, Gawlik B M, Easton P and Laspidou C 2021 An analytical framework to assess SDG targets within the context of WEFE Nexus in the Mediterranean region *Resour. Conserv. Recycl.* **164** 105205

Mancini G, Luciano A, Bolzonella D, Fatone F, Viotti P and Fino D 2021 A water-waste-energy Nexus approach to bridge the sustainability gap in landfill-based waste management regions *Renew. Sustain. Energy Rev.* **137** 110441

Mantziaris S, Iliopoulos C, Theodorakopoulou I and Petropoulou E 2017 Perennial energy crops vs. durum wheat in low input lands: economic analysis of a Greek case study *Renew. Sustain. Energy Rev.* **80** 789–800

Marinelli E, Radini S, Akyol Ç, Sgroi M, Eusebi A L, Bischetti G B, Mancini A and Fatone F 2021 Water–energy–food–climate Nexus in an integrated peri-urban wastewater treatment and reuse system: from theory to practice *Sustainable* **13** 10952

Markantonis V *et al* 2019 Can the implementation of the water-energy-food Nexus support economic growth in the Mediterranean region? The current status and the way forward *Front. Environ. Sci.* **7** 84

Martin-Gorriz B, Soto-García M and Martínez-Alvarez V 2014 Energy and greenhouse-gas emissions in irrigated agriculture of SE (southeast) Spain. Effects of alternative water supply scenarios *Energy* **77** 478–88

Martinez P, Blanco M and Castro-Campos B 2018 The water-energy-food Nexus: a fuzzy-cognitive mapping approach to support Nexus-compliant policies in Andalusia (Spain) *Water* **10** 664

Mayor B, López-Gunn E, Villarroya F I and Montero E 2015 Application of a water–energy–food Nexus framework for the Duero river basin in Spain *Water Int.* **40** 791–808

MedECC 2020 Climate and environmental change in the Mediterranean Basin—Current Situation and Risks for the Future *First Mediterranean Assessment Report* ed W Cramer, J Guiot and K Marini (Marseille: Union for the Mediterranean, Pan Bleu, UNEP/MAP) p 632

Melikoglu M and Cinel A M 2020 Food waste-water-energy Nexus: scrutinising sustainability of biodiesel production from sunflower oil consumption wastes in Turkey till 2030 *Environ. Technol. Innov.* **17** 100628

Merheb M, Moussa R, Abdallah C, Colin F, Perrin C and Baghdadi N 2016 Hydrological response characteristics of Mediterranean catchments at different time scales: a meta-analysis *Hydrol. Sci. J.* **61** 2520–39

Miglietta P, Morrone D and De Leo F 2018 The water footprint assessment of electricity production: an overview of the economic-water-energy Nexus in Italy *Sustainability* **10** 228

Moioli E, Salvati F, Chiesa M, Siecha R T, Manenti F, Laio F and Rulli M C 2018 Analysis of the current world biofuel production under a water–food–energy Nexus perspective *Adv. Water Resour.* **121** 22–31

Moreda G P, Muñoz-García M A, Alonso-García M C and Hernández-Callejo L 2021 Techno-economic viability of agro-photovoltaic irrigated arable lands in the EU-Med region: a case-study in Southwestern Spain *Agronomy* **11** 593

Nadal A, Llorach-Massana P, Cuerva E, López-Capel E, Montero J I, Josa A, Rieradevall J and Royapoor M 2017 Building-integrated rooftop greenhouses: an energy and environmental assessment in the Mediterranean context *Appl. Energy* **187** 338–51

Nikolaou T, Stavrakakis G S and Tsamoudalis K 2020 Modeling and optimal dimensioning of a pumped hydro energy storage system for the exploitation of the rejected wind energy in the non-interconnected electrical power system of the Crete Island, Greece *Energies* **13** 2705

Odabaş Baş G and Aydınalp Köksal M 2022 Environmental and techno-economic analysis of the integration of biogas and solar power systems into urban wastewater treatment plants *Renew. Energy* **196** 579–97

Pacetti T, Lombardi L and Federici G 2015 Water–energy Nexus: a case of biogas production from energy crops evaluated by water footprint and life cycle assessment (LCA) methods *J. Clean. Prod.* **101** 278–91

Page M J *et al* 2021 The PRISMA 2020 statement: an updated guideline for reporting systematic reviews *Syst. Rev.* **10** 89

Pahl-Wostl C 2007 The implications of complexity for integrated resources management *Environ. Model. Softw.* **22** 561–9

Papadopoulou C-A, Papadopoulou M, Laspidou C, Munaretto S and Brouwer F 2020 Towards a low-carbon economy: a Nexus-oriented policy coherence analysis in Greece *Sustainability* **12** 373

Papadopoulou M P and Vlachou A 2022 Conceptualization of NEXUS elements in the marine environment (Marine NEXUS) *Euro-Mediterr. J. Environ. Integr.* **7** 399–406

Papapostolou C M, Kondili E M, Zafirakis D P and Tzanes G T 2020 Sustainable water supply systems for the islands: the integration with the energy problem *Renew. Energy* **146** 2577–88

Pérez-Sánchez M, Fernandes J F P, Branco P J C, López-Jiménez P A and Ramos H M 2021 PATs behavior in pressurized irrigation hydrants towards sustainability *Water* **13** 1359

Pérez-Sánchez M, Sánchez-Romero F, Ramos H and López-Jiménez P 2016 Modeling irrigation networks for the quantification of potential energy recovering: a case study *Water* **8** 234

PNUE/PAM-Plan Bleu 2009 *PNUE/PAM-Plan Bleu : Etat de l'environnement et du développement en Méditerranée* (PNUE/PAM-Plan Bleu)

Pradeleix L, Roux P, Bouarfa S, Jaouani B, Lili-Chabaane Z and Bellon-Maurel V 2015 Environmental impacts of contrasted groundwater pumping systems assessed by life cycle assessment methodology: contribution to the water-energy Nexus study *Irrig. Drain.* **64** 124–38

Psomas A, Dagalaki V, Panagopoulos Y, Konsta D and Mimikou M 2016 Sustainable agricultural water management in Pinios River basin using remote sensing and hydrologic modeling *Proc. Eng.* **162** 277–83

Psomas A, Vryzidis I, Spyridakos A and Mimikou M 2021 MCDA approach for agricultural water management in the context of water–energy–land–food Nexus *Oper. Res.* **21** 689–723

Purwanto A, Sušnik J, Suryadi F X and de Fraiture C 2021 Water-energy-food Nexus: critical review, practical applications, and prospects for future research *Sustainability* **13** 1919

R Core Team 2022 R: a language and environment for statistical computing (R Foundation for Statistical Computing) (available at: www.R-project.org/)

Rabhy O O, Adam I G, Elsayed Youssef M, Rashad A B and Hassan G E 2019 Numerical and experimental analyses of a transparent solar distiller for an agricultural greenhouse *Appl. Energy* **253** 113564

Rahmane A, Benelbar M and Traich M 2021 The Nexus between sustainable energy and ecological footprint: evidence from Algeria *Sustain. Sci. Pract. Policy* **17** 323–33

Riccaboni A, Antonelli M and Stanghellini G 2022 Partnership for research and innovation in the Mediterranean area and the promotion of a Nexus approach *Connecting the Sustainable Development Goals: The WEF Nexus. Sustainable Development Goals Series* ed L Cavalli and S Vergalli (Cham: Springer) pp 13–19
Ringler C, Bhaduri A and Lawford R 2013 The Nexus across water, energy, land and food (WELF): potential for improved resource use efficiency? *Curr. Opin. Environ. Sustain.* **5** 617–24
Rockström J *et al* 2009 Planetary boundaries: exploring the safe operating space for humanity *Ecol. Soc.* **14** art32
Rodrigues F, Silva-Afonso A, Pinto A, Macedo J, Santos A S and Pimentel-Rodrigues C 2020 Increasing water and energy efficiency in university buildings: a case study *Environ. Sci. Pollut. Res.* **27** 4571–81
Rose M E and Kitchin J R 2019 pybliometrics: scriptable bibliometrics using a Python interface to Scopus *SoftwareX* **10** 100263
Saladini F *et al* 2018 Linking the water-energy-food Nexus and sustainable development indicators for the Mediterranean region *Ecol. Indic.* **91** 689–97
Salah A H, Hassan G E, Fath H, Elhelw M and Elsherbiny S 2017 Analytical investigation of different operational scenarios of a novel greenhouse combined with solar stills *Appl. Therm. Eng.* **122** 297–310
Santin M, Chinese D, De Angelis A and Biberacher M 2020 Feasibility limits of using low-grade industrial waste heat in symbiotic district heating and cooling networks *Clean Technol. Environ. Policy* **22** 1339–57
Sargentis G-F, Siamparina P, Sakki G-K, Efstratiadis A, Chiotinis M and Koutsoyiannis D 2021 Agricultural land or photovoltaic parks? The water–energy–food Nexus and land development perspectives in the Thessaly plain, Greece *Sustainability* **13** 8935
Sesma-Martín D and Puente-Ajovín M 2022 The environmental Kuznets curve at the thermoelectricity-water Nexus: empirical evidence from Spain *Water Resour. Econ.* **39** 100202
Sesma-Martín D and Rubio-Varas M D M 2019 The weak data on the water–energy Nexus in Spain *Water Policy* **21** 382–93
Snyder H 2019 Literature review as a research methodology: an overview and guidelines *J. Bus. Res.* **104** 333–9
Solera A, Pedro-Monzonís M, Andreu J and Estrela T 2018 Analysing hydropower production in stressed river basins within the SEEA-W approach: the Jucar River case *Hydrol. Res.* **49** 528–38
Soto-García M, Martin-Gorriz B, García-Bastida P A, Alcon F and Martínez-Alvarez V 2013 Energy consumption for crop irrigation in a semiarid climate (south-eastern Spain) *Energy* **55** 1084–93
Sušnik J, Chew C, Domingo X, Mereu S, Trabucco A, Evans B, Vamvakeridou-Lyroudia L, Savić D, Laspidou C and Brouwer F 2018 Multi-stakeholder development of a serious game to explore the water-energy-food-land-climate Nexus: the SIM4NEXUS approach *Water* **10** 139
Sušnik J and Staddon C 2021 Evaluation of water-energy-food (WEF) Nexus research: perspectives, challenges, and directions for future research *J. Am. Water Resour. Assoc.* **58** 1189–98
Taguta C, Senzanje A, Kiala Z, Malota M and Mabhaudhi T 2022 Water-energy-food Nexus tools in theory and practice: a systematic review *Front. Water* **4** 837316
Teitelbaum Y, Yakirevich A, Gross A and Sorek S 2020 Simulations of the water food energy Nexus for policy driven intervention *Heliyon* **6** e04767
Teotónio C, Rodríguez M, Roebeling P and Fortes P 2020 Water competition through the 'water-energy' Nexus: assessing the economic impacts of climate change in a Mediterranean context *Energy Econ.* **85** 104539
Tobarra M A, López L A, Cadarso M A, Gómez N and Cazcarro I 2018 Is seasonal households' consumption good for the Nexus carbon/water footprint? The Spanish fruits and vegetables case *Environ. Sci. Technol.* **52** 12066–77
Toboso-Chavero S, Nadal A, Petit-Boix A, Pons O, Villalba G, Gabarrell X, Josa A and Rieradevall J 2019 Towards productive cities: environmental assessment of the food-energy-water Nexus of the urban roof mosaic *J. Ind. Ecol.* **23** 767–80
Tovar-Facio J, Guerras L S, Ponce-Ortega J M and Martín M 2021 Sustainable energy transition considering the water-energy Nexus: a multiobjective optimization framework *ACS Sustain. Chem. Eng.* **9** 3768–80
UNESCO, FAO 1963 Bioclimatic map of the Mediterranean zone
Union for the Mediterranean 2020 UfM water policy framework for actions 2030 (UfM Secretariat)
Valenti F, Liao W and Porto S M C 2020 Life cycle assessment of agro-industrial by-product reuse: a comparison between anaerobic digestion and conventional disposal treatments *Green Chem.* **22** 7119–39
van Eck N J and Waltman L, 2010. VOSViewer: visualizing scientific landscapes *Software* (available at: www.vosviewer.com)
van Gevelt T 2020 The water–energy–food Nexus: bridging the science–policy divide *Curr. Opin. Environ. Sci. Health* **13** 6–10
Viccaro M, Caniani D, Masi S, Romano S and Cozzi M 2022 Biofuels or not biofuels? The "Nexus Thinking" in land suitability analysis for energy crops *Renew. Energy* **187** 1050–64
Villamayor-Tomas S 2018 Polycentricity in the water–energy Nexus: a comparison of polycentric governance traits and implications for adaptive capacity of water user associations in Spain *Environ. Policy Gov.* **28** 252–68
Villamayor-Tomas S, Grundmann P, Epstein G, Evans T and Kimmich C 2015 The water-energy-food security Nexus through the lenses of the value chain and the institutional analysis and development frameworks *Water Altern.* **8** 735–55
Villar-Navascués R, Ricart S, Gil-Guirado S, Rico-Amorós A M and Arahuetes A 2020 Why (not) desalination? Exploring driving factors from irrigation communities' perception in South-East Spain *Water* **12** 2408
Viola A, Franzitta V, Trapanese M and Curto D 2016 Nexus water & energy: a case study of wave energy converters (WECs) to desalination applications in Sicily *Int. J. Heat Technol.* **34** S379–S386
Wickham H 2016 *Ggplot2: Elegant Graphics for Data Analysis* (Springer)
Wiegleb V and Bruns A 2018 What is driving the water-energy-food Nexus? Discourses, knowledge, and politics of an emerging resource governance concept *Front. Environ. Sci.* **6** 128
Willaarts B A, Lechón Y, Mayor B, de la Rúa C and Garrido A 2020 Cross-sectoral implications of the implementation of irrigation water use efficiency policies in Spain: a Nexus footprint approach *Ecol. Indic.* **109** 105795
Xydis G, Strasszer D, Avgoustaki D D and Nanaki E 2021 Mass deployment of plant factories as a source of load flexibility in the grid under an energy-food Nexus. A technoeconomics-based comparison *Sustain. Energy Technol. Assess.* **47** 101431
Yaykiran S, Cuceloglu G and Ekdal A 2019 Estimation of water budget components of the Sakarya river basin by using the WEAP-PGM model *Water* **11** 271
Yoon H and Saurí D 2019 'No more thirst, cold, or darkness!'—social movements, households, and the coproduction of knowledge on water and energy vulnerability in Barcelona, Spain *Energy Res. Soc. Sci.* **58** 101276

Yoon H, Saurí D and Rico A 2022 The water-energy Nexus in hotels and recreational activities of a mass tourism resort: the case of Benidorm *Curr. Issues Tour.* **25** 592–610

Yoon H, Saurí D and Rico Amorós A 2018 Shifting scarcities? The energy intensity of water supply alternatives in the mass tourist resort of Benidorm, Spain *Sustainability* **10** 824

Zambrano-Prado P, Muñoz-Liesa J, Josa A, Rieradevall J, Alamús R, Gasso-Domingo S and Gabarrell X 2021 Assessment of the food-water-energy Nexus suitability of rooftops. A methodological remote sensing approach in an urban Mediterranean area *Sustain. Cities Soc.* **75** 103287

Zhang C, Chen X, Li Y, Ding W and Fu G 2018 Water-energy-food Nexus: concepts, questions and methodologies *J. Clean. Prod.* **195** 625–39

Ziogou I and Zachariadis T 2017 Quantifying the water–energy Nexus in Greece *Int. J. Sustain. Energy* **36** 972–82

Zografos C 2017 Flows of sediment, flows of insecurity: climate change adaptation and the social contract in the Ebro Delta, Catalonia *Geoforum* **80** 49–60

Zucchinelli M, Spinelli R, Corrado S and Lamastra L 2021 Evaluation of the influence on water consumption and water scarcity of different healthy diet scenarios *J. Environ. Manage.* **291** 112687