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Characterizing and Defining of Designing Sustainable Product-Service Systems Applied to Distributed Water-Energy-Food Nexus

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The Water-Energy-Food (WEF) Nexus significantly and effectively address sustainability issues internationally. However, there has been little attention paid to the WEF Nexus challenges related to sustainable livelihoods, such as resource access, resource security, and resource utilization. Given the need to establish design research, policy formulation, and resource management based on end-user needs, new research hypotheses and available models must be proposed on a small-scale scale of households and communities. This paper combines the Sustainable Product-Service System (SPSS) and Distributed Economies (DE), two prospective and intertwined models combining environmental, social, and economic sustainability with the WEF Nexus approach, to emphasize the shift to small-scale and highly localized WEF systems and the product and service system based on the satisfaction unit, i.e., designing SPSS applied to Distributed WEF Nexus. This paradigm shift is presented and detailed in an 11-dimensional canvas with an analytical, conceptual research approach to help to define and analyze the characteristics of existing solutions and promote innovative ideas or scenarios in a sustainable WEF nexus. The new 11-dimensional canvas tool, in particular, is thought to have the potential to become a basic research analysis and innovative strategic tool in this field after being tested and evaluated by forty companies, experts, and designers in China and Italy. Finally, despite considerable implementation obstacles, this innovative application of multi-mode integration still has the potential for win-win sustainability, to meet human needs for clean water, safe energy, and sufficient food, ultimately accelerating the transition to a sustainable society.

Keywords: sustainability design, sustainable product-service system, distributed water-energy-food nexus, dimension characterizing, design strategy

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1 INTRODUCTION

Water is crucial for daily use and has no substitute. Sufficient access to water and energy are not available to everyone worldwide. As per different data, there are 2.2 billion (WHO&UNICEF, 2019), 770 million (IEA, 2020), 2.6 billion, and two billion (FAO, 2020) people who do not have access to safe drinking water or electricity services. To achieve sustainable social development, it is particularly critical and urgent to effectively solve resource challenges, such as water, energy, and food (Biggs et al., 2015; Chang et al., 2016; Liu N et al., 2021). The world's population is projected to grow from

7.7 billion in 2019 to 8.5 billion in 2030 (10% increase), and further to 9.7 billion in 2050 (26%) and to 10.9 billion in 2100 (42%) (United Nations, 2019); this will have an extra burden on industrialization, economic change, and globalization as it will cause the global demand for water, energy, and food to grow beyond the carrying capacity of the earth (de Andrade Guerra et al., 2020). Water is important for energy production and the production of food requires the combined effect of water and energy. The global energy demand will grow by 50%, food demand will grow by 60% (FAO, 2020; UEIA, 2020), and the time proportion of the population in water-scarce areas in the world will be around 52% (Kölbel et al., 2018). Growing scarcity can worsen access to basic needs and threaten the integrity of ecosystems; integrated resources management, or better still, a system design approach to water, energy, and food supply, can effectively address and halt these trends. This has been highlighted in the decision-making process owing to the complex relationships between three elements (Bazilian et al., 2011; Howells et al., 2013; Sohail et al., 2021a; Sohail et al., 2021b; Sharma et al., 2021; Sohail et al., 2021), i.e., adopting the systematic way to design, develop, and manage the nexus (Bazilian et al., 2011; Leck et al., 2015; Keairns et al., 2016; Kurian, 2017; Weitz et al., 2017; Namany et al., 2019). The WEF Nexus has become the core of the discussion on the formulation and follow-up monitoring of the Sustainable Development Goals, focusing on Goal 6 (clean water for all), Goal 7 (energy for all), and Goal 2 (food security for all). The first step for achieving these goals could be to build a well-coordinated nexus system (Obersteiner et al., 2016; Yen et al., 2017; Mercure et al., 2019; Simpson and Jewitt, 2019; Borowski, 2021; Sohail et al., 2021c; Sohail et al., 2021d). In the current year, the WEF nexus, with a new method to clarify the complex interactions between multiple resource systems, has been developing rapidly in academic and scientific research (Endo et al., 2017; Liu et al., 2017; Albrecht et al., 2018; Mabrey and Vittorio, 2018). However, the scientifically applicable models, frameworks, and methods to handle the WEF nexus issues applying systematic analytical thinking still need to be further enriched. In the LeNSin project-the International Learning Network of networks on Sustainability (EU Erasmus+, 2015–2020) - researchers have proposed the SPSS and the DE mode, which join environmental, social, and economic sustainability; this has been practiced and validated by many case studies and design experience that were applied in various circumstances around the world (especially in low/middle-income contexts). The SPSS and the DE model are considered to be a win-win sustainable opportunity for all (Sohail et al., 2014; Vezzoli et al., 2014, 2017; Kohtala, 2015; Emili et al., 2016; Petrulaityte et al., 2017; Sohail et al., 2019a; Sohail et al., 2019; Nasrullah et al., 2021). The identification of designing SPSS applied to Distributed WEF Nexus characterizing was carried out using the analytical and conceptual method (Meredith, 1993; Wacker, 1998; Sohail et al., 2013). Establishing new insights by logically developing the relationships of defined concepts is the focus of this approach; in the paper, we determined the different discriminatory dimensions of Distributed WEF Nexus and SPSS. Focus on key dimensions, five dimensions of SPSS and nine dimensions of Distributed WEF Nexus are grouped and analyzed to build the original conceptual model, i.e., the 11-dimensional canvas, that could explain the characteristics and benefits related to the attributes of SPSS applied to Distributed WEF Nexus. This paper has significant value and helps to fill the knowledge gap about the combination of those three models. The objectives of this research were: 1) To characterize the key role in designing SPSS applied to Distributed WEF Nexus; 2) to characterize the characteristics and models of SPSS applied to Distributed WEF Nexus, in particular, in low and middle-income environments; 3) to discuss critical factors and challenges characterizing the SPSS applied to DE in the WEF Nexus approach; and 4) consider the applications of these models to promote sustainability for all.

2 METHODOLOGY

2.1 Data Collection

After developing the 11-dimensional canvas, it was presented to companies, experts, and practitioners in China and Italy between May and July 2021. In this study, there were 40 people (12 from six different companies that focus on new energy, water, and food, 18 experts including eight professors on sustainability, five from a national research center on innovation and sustainability, five from a strategic design consultancy, and 10 designers who had over 6 years of experience engaged in product and/or service design from famous design companies) participated in the testing activities. Testing activities assessed various aspects of the 11-dimensional canvas: the completeness and inclusion of all possible characteristics, the clarity and usability, and the effectiveness. First, through a 1 h demonstration, the interviewees were presented and introduced to the SPSS model applied to the distributed WEF Nexus (Stein et al., 2018; Al-Sumaiti et al., 2020).

2.2 Sustainability Potential Models

2.2.1 SPSS Applied to DE

Since the late 1990s, the concept of the SPSS has been focused on as one of the most promising models for innovation based on the shift from traditional product or service sales to products and services' combination to address specific customer requirements (Goedkoop et al., 1999; Cooper and Evans, 2000; Mont, 2001; UNEP, 2002; Tukker and Tischner, 2006; Baines et al., 2007). When the product-service system (PSS) repositions unsustainable production and consumption patterns to reduce the impact of "satisfied units" on the environment, it is called an Eco-efficient PSS (Manzini & Vezzoli, 2003); when sustainable benefits are also related to social ethics, it is called SPSS (Vezzoli et al., 2015; Mahfooz et al., 2017; Vezzoli et al., 2018; Mahfooz et al., 2019). DE is a concept proposed as a response to the present industrial production system, which can accelerate the development of small-scale, decentralized, and flexible units that are connected in coordination and utilize local resources (Johansson et al., 2005). In addition, DE is used in the innovation of regional sustainable development strategies. Therefore, "area" is considered (IIIEE, 2009) as a small network entity integrated into the network, which has the advantage of being more flexible

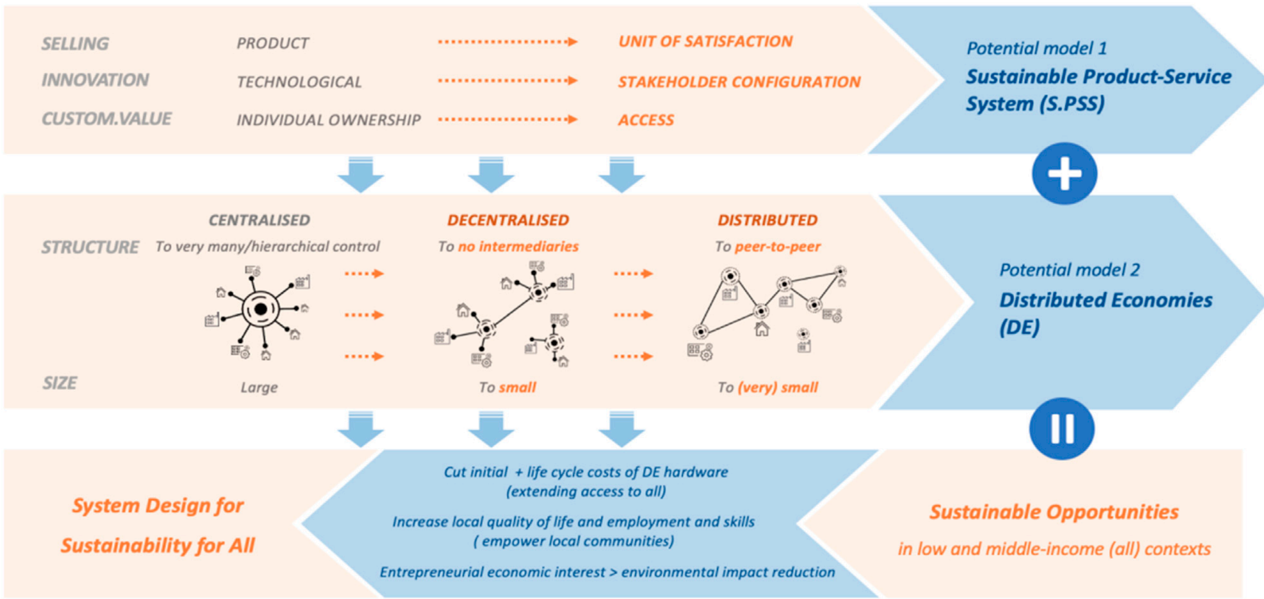

FIGURE 1 | The win-win model of SPSS applied to DE (LeNSin, 2015–2020).

and adapting to changes. In the LeNSin project, DE is defined as giving end-users control over basic activities and optimizing the point-to-point network structure of production and sales by sharing resources, commodities, information and knowledge, realizing a paradigm shift from a centralized large-scale production unit and distribution system to a small local production unit. The definition has so far been reorganized as follows (LeNSin, 2019): The SPSS and the DE models, or better still their combination, have been considered as promising methods to tackle economic, environmental, and socio-ethical issues in low/middle-income (all) contexts (Vezzoli et al., 2014; Jiang et al., 2021). The SPSS applied to DE can reduce the initial (capital) cost of DE hardware purchase (which may not be affordable) and the operating cost of DE hardware maintenance, repair, and upgrade (which may lead to interruption of use), improve the level of local employment and related skills, and increase the economic income of producers/providers, to design DE production units and products with low environmental impact, and achieve the sustainable development to obtain resources, goods, and services (LeNSin, 2015–2020) (**Figure 1**).

2.3 The WEF Nexus

The WEF nexus provides an analytical framework for studying the dynamic interaction of water, energy, and food resource flow, using a systematic method to analyze the interaction of stakeholders, and proposing a very effective sustainable development strategy, which has been recognized by more and more international organizations and academia. (Meadows et al., 1972; Levison et al., 1977; Allan, 2003; Qadir et al., 2007; Endo et al., 2017; Liu et al., 2017). However, the WEF nexus framework was first proposed in the World Economic Forum (2011) and defined as a major risk for global economic and social development. Then at the Nexus conference in Bonn, Hoff, (2011), it took into account global trends and potential areas of action and improved the framework with the availability of water resources as the center. The World Economic Forum (WEF) nexus is embedded in natural, architectural, institutional, and governance systems, and an ecosystem-based framework was proposed by the International Institute for Sustainable Development, 2013. Finally, the FAO framework emphasized the connections between humans and natural systems to promote sustainable development based on a 2014 resource-focused framework. Although the WEF Nexus has yet to form a definitive definition, owing to the multiple research scales and short development period, the understanding of the WEF Nexus can be summarized as a combination of the core and peripheral systems (**Figure 2**). The core WEF Nexus system illustrates the inside-relevance of water, energy, and food, that reflects the interdependence and mutual restriction relationship between water, energy, and food resources. For example. the storage, extraction, transportation, treatment, and use of water requires energy consumption, the production and preparation of energy (mining, oil refining, hydropower) and distribution and utilization (heating and refrigeration) of energy need the support of water resources, and food production requires water and energy consumption from irrigation to processing and distribution.

2.4 Characterizing Dimensions Analysis

Through the definition of characterizing dimensions of the two potential models, the characteristics analysis and research that integrates the contribution of SPSS to Distributed WEF Nexus could be studied. Dimensions represent changes in attributes and provide information about the specificity and scope of certain concepts (Corbin & Strauss, 2014). SPSS and DWEFN

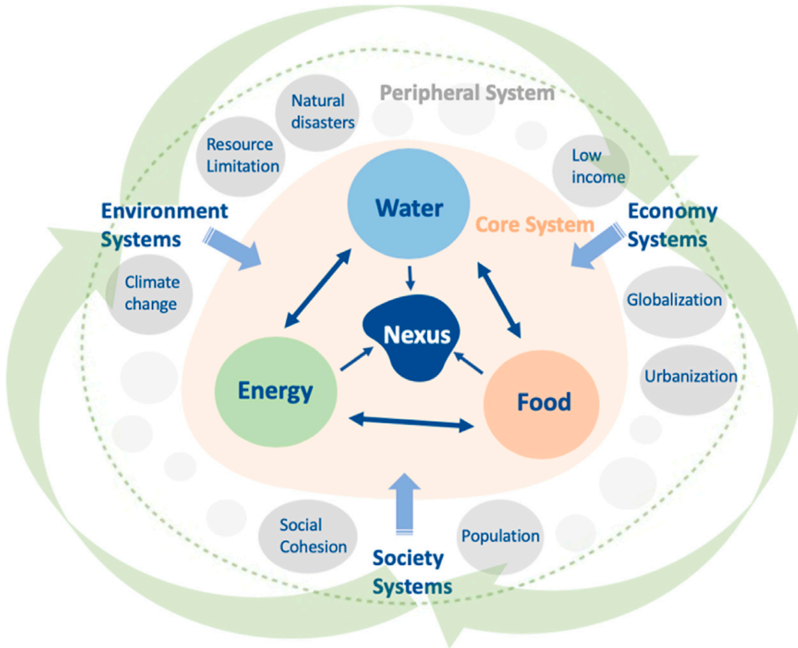

FIGURE 2 | The WEF nexus system combination of the core system and peripheral system.

characterizing dimensions are variants of the characterization components used to describe the model in the study.

2.5 Characterizing Distributed WEF Nexus

Distributed WEF Nexus and sustainable WEF supply are related concepts in the evolution of access to water, energy, and food. The distribution and WEF nexus are increasingly important in achieving sustainable development. In the distributed WEF nexus model, the foundation and key services of water, food, and energy are close to the demand point, for example, a household balcony greenhouse equipped with solar panels and a rainwater purification system, and customers are both consumers and producers of water, energy, and food-related goods. However, Distributed WEF Nexus does not need to define the types of resources used but emphasizes resource acquisition sustainability, effectively using cross-sectoral and increasing interconnections in space and time to achieve sustainable resource acquisition and improve resource utilization efficiency. Improved water, energy, and food security (LeNSin 2015–2020). The Distributed WEF Nexus changes the system size from a large centralized production and distribution system to a small-scale production system with a high degree of localization, as well as the hierarchical structure to a peer-to-peer distributed network. This can increase the system's openness, transforming it from a closed one-way network to a hybrid open, collaborative network, as well as improve the system's ability to reestablish equilibrium in the face of change and promote a more flexible response to user needs. Furthermore, consumers are also producers in Distributed WEF Nexus, allowing for a shift from standardized to customized production. However, a clear presentation that characterizes Distributed WEF Nexus appears to be missing. To emphasize the paradigm shift to Distributed WEF Nexus, the following definition is proposed: Through a literature review of WEF Nexus, we found that although the research on WEF Nexus has varying descriptions, the four dimensions of a WEF Nexus model are recognized by some researchers (Garcia and You, 2016; Guta et al., 2017; Terrapon-Pfaff et al., 2018; Abulibdeh and Zaidean, 2020) in system modeling, policy research, or practice. The spatial or geographical scale refers to the definition of system boundary for WEF Nexus, i.e., the geographic level of applicability for the nexus, from a small-scale household or individual to a global scale (Garcia et al., 2019; Abulibdeh and Zaidan, 2020; Sharma et al., 2021a; Jain et al., 2021; Allain et al., 2022). Each scale has its supply chain of water, energy, and food; each scale is connected to others (Putra et al., 2020). Stakeholder refers to the roles involved in cross-departmental collaboration and competition in the WEF Nexus system related to the supply chain. Different hierarchies of stakeholders (individual, enterprise, manufacturers, governments, etc.) have various sustainability priorities. Industrial and agricultural producers are mainly focused on income and prices, households are focused on financial security and health, and governments are concerned with fiscal policy and environmental and social factors (Hoolohan et al., 2018; Garcia, 2019; Küblböck et al., 2021). Planning and properly defining these goals is one of the core challenges of optimizing WEF Nexus (Endo et al., 2018; Zhao et al., 2019; Melloni et al., 2020). Risk assessment is an event or activity that has a significant adverse impact on the WEF nexus system that has been considered as the key indicator for assessing system risk and achieving sustainability (Abulibdeh and Zaidan, 2020; de Andrade Guerra et al., 2020; Yi et al., 2020; Shahab et al.,

TABLE 1 | The description and details of dimensions characterizing Distributed WEF Nexus.

Dimension	Description	Details
System structure	It could be characterized to summarize the interaction between stakeholders in WEF nexus system belonging to which hierarchical structure, to offer, transfer or gain the water, energy, food production/ supply	Stand-alone household WEF nexus; Network entrepreneur structure of WEF nexus; Network to the network community structure of WEF nexusetc.
System breadth	The nexus range or resources included. Due to the inseparable connection between the WEF nexus system and the outside resource and eco-environments, the nexus can include more resources or factors	Water, energy, food; Water, energy, land, food (Ringler et al., 2013); Water, energy, climate, food (Beck and Villarroel Walker, 2013); Ecosystem, water, food, energy (Karabulut et al., 2016)etc.
Payment structure	It represents the value proposition of WEF solutions provided to customers in the offering model, that is, the combination of goods and services that the customer is willing to pay for and the payment structure	Pay-to-purchase (product-related service; advice; training; consultancy; additional services) (Gaiardelli et al., 2014); Pay rent; pay rent/sharing/ pooling; Pay-per-period; Pay by time; Pay-per-use; In-kind contribution; Hybrid payment (Emili et al., 2016; Petrulaityte et al., 2017; Bacchetti, 2018)etc.
Capital financing	Represents the means and/or organizations of capital providing and related cost recovering and revenue supporting for the WEF nexus system	Governmental subsidies, donations, private loans, micro-finance institutionetc.
Ownership	Refers to who owns the services and/or products related to the solutions offered in Distributed WEF nexus system	Customer or Provider
Organization form	The nature of institution providing the WEF nexus system solution	Public sector-based, NGO, community, PPP/hybrid, private sector-basedetc.
Operation	It refers to who operates and manages those services and/or products related to the solutions offered in Distributed WEF nexus system	Customer/Provider
Customer	The nature of the end-users, it should be as close to end consumers' needs as possible on the geographical scale in Distributed WEF nexus system	Household, private company, community, or other productive activities
Risk assessment	Refers to the events or activities that have a substantial negative effect on inside-relevance and outside-relevance of Distributed WEF Nexus system	Population growth, economic risk, extreme weather, conflicts, agriculture, technology, policy, etc. (Hoff, 2011; Lawford et al., 2013; Abulibdeh and Zaidan, 2020)

2016). System breadth indicates the nexus range of resources included. Due to the inseparable connection between the WEF nexus system and the outside resource and eco-environments, the nexus can include more resources or factors, like livelihoods (Biggs et al., 2015; Rasool et al., 2017), climate (Beck and Villarroel Walker, 2013; Sohail et al., 2014a; Sohail et al., 2015; Lan et al., 2021; Liu Y. et al., 2021), land (Ringler et al., 2013; Muhammad et al., 2014; Chai et al., 2021), and so on. Therefore, we propose nine descriptive dimensions for Distributed WEF Nexus (**Table 1**) that capture and combine the related dimensions in the publications from a supplementary and unified perspective to catch the benefits of distributed structure and cooperation of WEF nexus.

2.6 Dimensions of SPSS Applied to Distributed WEF Nexus

Three major SPSS approaches to system innovation that are rooted in a satisfaction-based economic model, stakeholder interaction-based innovations, and the intrinsic eco-efficiency potential have been studied and listed (Vezzoli et al., 2014): Product-oriented SPSS, User-oriented SPSS, Result-oriented SPSS. This classification also refers to the orientation of SPSS offering, ownership, operation, and decision-making power, provider and customer interaction, and sustainability potential involved in SPSS innovation. SPSS offering, also known as value proposition,corresponds to a series of products or services provided for users in the system, as well as the substantive value that users are willing to pay for. The operation needs to manage, operate, and maintain the products of the system, which can be customers (i.e., the end-users, individuals, communities, entrepreneurs, etc.) or providers. The nature of the user's and supplier's interaction can be either a buyer-seller relationship (transaction-based in a product-oriented SPSS) or building and continuing a closer relationship (relationship-based in a use-oriented and result-oriented SPSS). Based on three principal forms of innovative stakeholder configuration, product provision is combined with product lifecycle services to users, a support platform is provided for users, and the final result is provided to users.

The SPSS model's main characteristics are represented by the five dimensions listed above. Scholars generally agree with the previously proposed SPSS classification and dimension proposals (Manzini and Vezzoli, 2003; Tukker, 2004; Gaiardelli et al., 2014; Vezzoli et al., 2015; Reigado et al., 2017). The SPSS model is extensively used in the LeNSin project and has gained diverse features via practice and application to a variety of Sustainable challenge scenarios in China, Britain, Milan, India, Brazil, and other areas. It can be used in specific fields, like distributed manufacturing and distributed information and knowledge, as well as in distributed design and distributed software. For the range of this paper, these SPSS dimensions or distributed WEF nexus dimensions alone are not suitable for describing the specific characteristics of SPSS applied to DWEFN. The Distributed WEF Nexus changes the system size from a large centralized production and distribution system to a small-scale production system with a high degree of localization, as well as the hierarchical structure to a peer-to-peer distributed network. This can increase the system's openness, transforming it from a closed one-way network to a hybrid open, collaborative network, as well as improving the system's ability to reestablish equilibrium in the face of change and promote a

TABLE 2 | The dimensions characterizing SPSS and Distributed WEF Nexus.

SPSS dimensions	DWEF nexus dimensions	SPSS + DWEF nexus dimensions
	System structure	1. System structure
	System breadth	2. System breadth
SPSS offering	Payment structure	3. Payment structure
	Capital financing	4. Capital financing
Ownership	Ownership	5. Ownership
	Organization form	6. Organization form
Operation	Operation	7. Operation
	User	8. Customer
Provider/user relationship		9. Provider/user relationship
Sustainability potential		10. Sustainability potential
	Risk assessment	11. Risk assessment

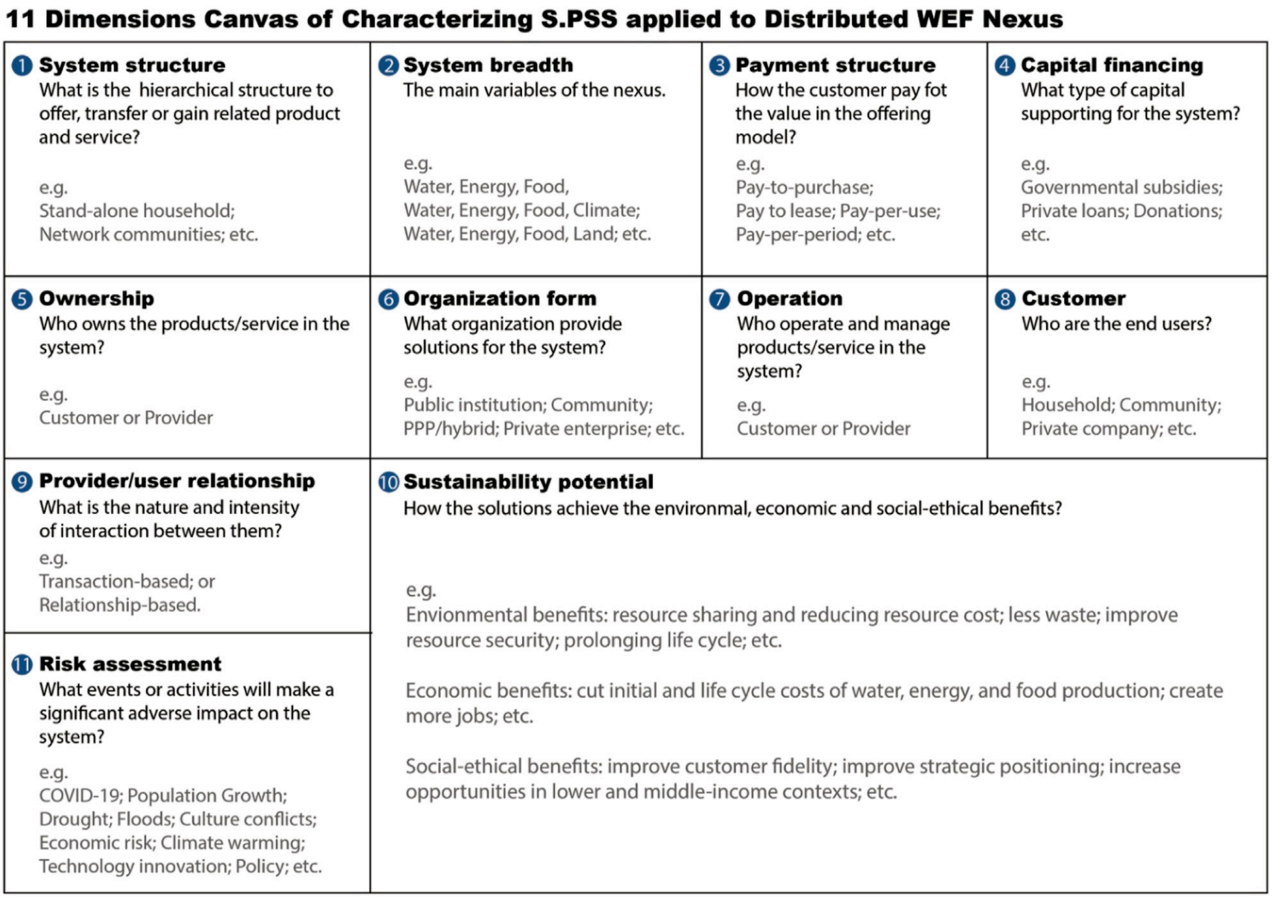

FIGURE 3 | The description and details of characterizing SPSS applied to Distributed WEF Nexus in 11 Dimensions Canvas.

more flexible response to user needs. Furthermore, consumers are also producers in Distributed WEF Nexus, allowing for a shift from standardized to customized production. However, related to this, we must recognize the complexity of this model: SPSS applied to DWEFN can propose solutions focused on providing access to energy, food, and water collaborative systems (i.e., Mini-grid for biomass gasifier, Micro Hydropower Station, and floating farm), products that food, energy, and water can be converted or utilized mutually (such as biogas stove, drip irrigation planting equipment and solar water pump), the combination of these products or system output energy, food and water resources related or collaborative solutions (such as bioenergy, hydroponic crops, etc.). To this purpose, we first examine the distinctive characteristics of

Distributed WEF Nexus and SPSS to discover which dimensions overlap and combine. We found 11 dimensions after clustering (as shown in **Table 2**) to characterize in designing SPSS applied to Distributed WEF Nexus. Then, we describe and detail the 11 dimensions in a visualized canvas to characterize in designing SPSS applied to Distributed WEF Nexus (**Figure 3**). This dimension-based descriptive form as a design tool (**Figure 3**) could be used in gathering the information needed to facilitate the generation of solutions and scenarios for sustainable system innovations related to SPSS applied to Distributed WEF Nexus, as well as defining and developing the most promising concept into a detailed version by the visualized canvas for its implementation.

Therefore, applying SPSS to Distributed WEF Nexus means a double paradigm shift in system structure and supply mode, which is: 1) from a centralized production and supply structure based on freshwater resources, non-renewable energy, and food supply to a distributed renewable resource of water, energy, and food supply structure. 2) The transition from the traditional product supply model based on product ownership to a product and service system based on "satisfactory units" to meet demand.

The system structure (dimension 1) is closely connected to target clients (dimension 8); usually, the self-contained structure is generally domestic systems, aimed at the personal customer (e.g., home biogas), WEF solutions shared over a network to groups of users (e.g., the green roof for storing rainwater and growing crops), or through network-to-network communication (e.g., community farms, mini-grids, micro-hydropower). The distributed structure of Distributed WEF Nexus, enabling locally based, renewable water, energy, and food resources, promotes democratization and equal distribution of resources. Using locally based renewable resources can support local social and economic growth, facilitate the supply of water, energy and food in everyday living, and increase revenue within the flexibility of the earth (refer to dimension 10, 11). However, the changing external environment will seriously impact the acquisition and utilization of WEF resources. For example, in 2021, influenced by the outbreak and spread of COVID-19, it accelerated the difficulty of food acquisition that might have pushed an additional 83–132 million into chronic hunger and slowed down the promotion of safe energy and clean water facilities (FAO, 2021), besides regional conflicts, economic changes, technology innovation, and adjustment of production structure (Nicola et al., 2020). More diverse nexus systems will be expanded through the risk assessment (dimension 11) of its main related factors (dimension 2) as many related factors as possible will be included in consideration of sustainable solutions, which will help follow-up researchers explore and open up new research fields.

However, the purchase and maintenance costs of related equipment or products (pumps, solar panels, biogas stoves, drip irrigation equipment, etc.) in Distributed WEF Nexus system are often a significant investment in low and middle-income contexts, though governmental subsidies, donations, Private loans, micro-finance institution, and other approaches can effectively relieve the initial financial pressure of the household or community (dimension 3). By providing different combinations of service-oriented or results-oriented payment structures (dimension 4), such as pay-per-period, pay-per-time, pay-per-use, or in-kind contribution, the ownership changes from customer to the provider (dimension 5). Customers only need to pay attention to usage and service experience, and the provider is accountable for system operation, management, and the safeguarding and upgrading of equipment and products (dimension 7). As a result, the nature of the interplay between the user and supplier shifts to relationship-based (dimension 9), and the end-users will have easier access to WEF resources and fewer life cycle costs in the system.

In addition to solving the gap between local technology and business capabilities, the Distributed WEF Nexus model also shows the necessity of a service-based offering model (dimension 7) that provides a series of skill and knowledge training for local households and communities to create job opportunities and enhance the vitality of local economies. The provider of Distributed WEF Nexus system solutions can be a public sector-based institution (government, utility), private sector-based organization (private or local enterprises), a hybrid, or a Private Public Partnership (PPP) comprised of several various parties. The focus shifts from goods ownership to user-oriented or result-oriented to meet demand and overcome the constraints that affect everyone who can get the sustainable WEF Nexus supply, especially in low and middle-income situations.

3 RESULTS AND DISCUSSIONS

The 11 Dimensions canvas of characterizing SPSS applied to Distributed WEF Nexus has been practiced and tested by water, energy, and food companies, specialists, and designers, to test its completeness, usability, and effectiveness. The results are shown in **Table 3**.

3.1 Testing the Completeness

The first goal of the test campaign is to verify the integrity of the 11 dimensions canvas (i.e., to what extent it can cover all characteristics of SPSS applied to Distributed WEF Nexus). For this purpose, it involved participants to identify these 11 dimensions and see if they can point out the features and elements beyond these 11 dimensions. After introducing and describing the 11 dimensions, the respondent had around 1 h to rethink each dimension, combine their own experience within the field, and consider the case studies given for SPSS applied to Distributed WEF Nexus. Among all the interviewees, most of them indicate the main characteristics of value, stakeholders, interactions, system potential, and risk that have been covered. However, only three of them could distinguish other elements that were not contained in the identified dimensions: the specific interactions of all stakeholders involved in the nexus system have not been well defined (C6), the relevant information analysis of the material and equipment are missing (D3), and the technology innovation in the system has been neglected (E1). Following upgrades to the canvas tool, what has been noted will be refined and iteratively tested; the involvement of a broader range of

TABLE 3 | Questionnaire results.

Testing the completeness						
1. Could you think of other dimensions of SPSS applied to distributed WEF nexus that are not included in the 11 dimensions? If yes, which ones?	Yes:3 (7.5%, see section 6.1) No:37 (92.5%)					
Testing the usability	1: Not at all satisfied	2: Slightly satisfied	3: Moderately satisfied	4: Very satisfied	5: Completely satisfied	Average
2. To what extent are the descriptions of the 11 dimensions easy to comprehend (i.e. that each dimension's meaning is clear)?	0%	0%	2 (5%)	16 (40%)	22 (55%)	4.50
3. How easy are the 11 dimensions to use?	0%	0%	4 (10%)	22 (55%)	14 (35%)	4.25
4. To what extent would you use the 11 dimensions for your future research in the related topic?	0%	4 (10%)	6 (15%)	18 (45%)	12 (30%)	3.95
Testing the effectiveness	1: Not at all satisfied	2: Slightly satisfied	3: Moderately satisfied	4: Very satisfied	5: Completely satisfied	Average
5. To what extent do the 11 dimensions help you to comprehend the prospective benefits of applying SPSS to distributed WEF Nexus?	0%	3 (7.5%)	10 (25%)	22 (55%)	5 (12.5%)	3.725
6. To what extent are the 11 dimensions easy to use for existing cases?	0%	0%	4 (10%)	14 (35%)	22 (55%)	4.45
7. To what extent are the 11 dimensions easy to use for generating ideas?	0%	2 (5%)	7 (17.5%)	18 (45%)	13 (32.5%)	4.05

government sectors, enterprises, and experts, particularly from other disciplines and regional backgrounds, would help to provide stronger verification.

3.2 Testing the Usability

The second part of validating the usability entailed confirming whether participants could clearly understand the contents in the canvas, could use it without difficulty, and would be willing to continue using it in subsequent work and research.

The first step is to test the clarity of the canvas tool, that is, whether the meaning of each dimension is plain and easy to understand. The majority of interviewees rate this aspect very highly with an average of 4.5 out of total 5, "The text and keynotes given in the canvas enhance understanding of the content" (C9), "There are no disturbing information or images in the canvas, which is simple and easy to understand" (E5). However, a few designers (D3, D9) suggested that the graphics or images can present the description of the system structure (dimension 1) for a clearer understanding.

After 1 h of user experience, a large majority of participants reported no difficulty in using the tool (55% rated 4 = very satisfied and 35% rated 5 = Completely satisfied), "It is easy to distinguish the content of each dimension" (E13), and "it is easy to use with only text to fill in" (C12). However, two of the experts (E10, E16) expressed concern that the dimensional characteristics were described too simply and could easily lead to misunderstandings in team communication, suggesting that feedback on the use of the tool in teamwork should be supplemented in subsequent studies and trials. Satisfaction decreases when it comes to whether they will continue to use the tool in the future, four of them indicating that they are less likely to use it, "a preference for quantitative analysis of WEF resource input and output in a specific project and less focus on service and business model innovation" (C4, C11), "preferring a more visual and dynamic presentation to illustrate the cases and inspirations" (D3, D7). However, the remaining 75% of participants indicated that they were still willing to continue to use it, "it could simplify their difficulty in describing complex cases" (D6), "categorizing case information could facilitate comparative studies of different cases with same dimension level" (C1), and "it could help them to identify factors that were overlooked in research development" (C5).

3.3 Testing the Effectiveness

The assessment of effectiveness in the tool aims to show: 1) how well the toolkit contributes to the understanding of the potential benefits of this innovative model of SPSS applied to Distributed WEF Nexus, two] how well the tool supports the analysis of existing cases, and 3] how well it supports the generation of new ideas. 2) Most of the participants rated 11 dimensions ability to provide information about SPSS and WEF Nexus benefits≥4 (22 very satisfied and five completely satisfied), support the application of SPSS to WEF Nexus showing the transfer from the product-based offer model of water, energy, and food (e.g., irrigation, planting, pumping, power generation equipment) to product-service and even service-based sustainable offer models of WEF nexus system (e.g., reducing/avoiding initial investment, providing life-cycle service and cut related cost, community network, and individual capacity building). "Dimension 9 directly demonstrates the superiority of the SPSS model in the WEF Nexus system" (D3). "Dimension 10 gives a good indication of the potential benefits in the environmental, economic, and social level, but it takes some time to discern" (C1). On the contrary, "(there is a) lack of quantitative data analysis to directly assess specific economic benefits, inputs, and outputs to the environment and society" (C4). However, "dimensions 3 and 4 can reflect the weight of the initial financial investment and revenue scale in the system" (E13). A few participants also suggested that the synergistic nature of WEF be detailed in the system breadth or described separately, which would better represent the nexus system's benefits.

By analyzing the given case using the canvas tool, 55% of the participants agreed that the tool could fully support the analysis of the existing case, and only four participants rated 3 (Moderately satisfied). "More time needs to be spent identifying and defining the system structure as this part will not be directly shown in the presentation of the case" (C9), from the existing description of sustainability potential (dimension 10), "it is difficult to make an objective sustainable benefits comparison of the analyzed cases in terms of sustainability (dimension 10)" (E2), "the characteristics of the risk assessment (dimension 11) are given as a general list, which does not show priorities and may result in a generalized description" (C11). Other different views suggest that "the tool would be useful for basic research and pre-research stage" (E5), "an attempt could be made to introduce the tool in the classes of undergraduate and graduate students in related disciplines" (E8).

The 11 dimensions canvas can help researchers identify the key innovation factors in this innovative model that can facilitate the generation of new ideas. For example, it could be used to focus on decentralized models (dimension 1) to avoid wastage of WEF resources in distribution caused by intensive agriculture and production, or expanded to make connections with broader subsystems such as climate, biodiversity, or urban ecology (dimension 2) to contribute to a broader sustainability goal. It could also be used in identifying new business opportunities by choosing a different payment structure (dimension 3), replacing traditional sales to offer pay-per-use or pay-per-time to rent goods or equipment, and expanding business in low and middle-income situations, optimizing or improving the risk factors stated (dimension 11) to improve the sustainability and resilience of new ideas. Participants were asked to facilitate the generation of new ideas using the canvas tool in the last 30 min of the test to test our hypothesis. The respondents got an average score of 4.05. "Eleven dimensions helped to broaden ideas from different perspectives such as finance, stakeholder relations, service models, risk management, and social innovation, avoiding the dilemma of being in a fixed mindset" (C2), "the process of generating new ideas becomes structured" (C3), and "canvas can record the first thoughts of a new solution in a specific dimension, accelerating the formation of a complete solution" (D1).

4 BENEFITS ANALYSIS OF SPSS APPLIED TO DISTRIBUTED WEF NEXUS

The WEF system concept method, which links water, energy, and food, can finely comprehend and systematically study the interaction between the natural environment and human activities and will improve the level of cross-departmental and cross-scale coordinated management and the usage of the natural resources efficiency (Santos Da Silva et al., 2019). Also, the WEF nexus approach can help monitor and assess progress on the 2030 global agenda, making the implementation of SDGs more efficient and cost-effective (Naidoo et al., 2021). We can use the Nexus approach to evaluate and recognize trade-offs and create cooperation through feedback to achieve more integrated and cost-efficient planning, decision, implementation, supervision, and assessment (Radini et al., 2021). The use of distributed WEF networks and the SPSS model for the development, production, and use of these local WEF resources can empower local resources and increase local involvement in the mining, production, use, and disposal of these resources. It can reduce the difficulty of obtaining water, energy, food, and other resources in low and middle-income areas (Cipolletta et al., 2021), improve the fairness of supply and distribution, and all the efforts will contribute to the vision for a world free from poverty, hunger, and disease. As a win-win-win system, SPSS applied to Distributed WEF Nexus has the following potential:

4.1 Environmental Benefits

- Reduce waste and emissions in production and supply chains to minimize resource pressure. The production unit is often far from the end-user in centralized production, and the hidden environmental and social costs are relatively high. But the Distributed WEF Nexus supply system is built near the end-user to reduce the environmental impact of transportation and packaging.
- Extend product life-cycle and reduce environmental impact; Compared with traditional product offer models, SPSS usually means changes in ownership structure, aims to extend the product life-cycle, and provide life-cycle services for maintenance, repair, and replacement, delaying the replacement and production of new products, thereby minimizing the environmental impact. In addition, it provides higher economic benefits with white products, such as promoting the intensive use of products through sharing.
- Improve resource utilization while minimizing environmental hazards and impacts. The recycling of resources within the distributed WEF Nexus system (e.g., the wastewater could be used as irrigation water) can reduce the disposal costs. Simultaneously, the SPSS model uses different strategies to reduce transportation, distribution, minimize resource consumption, reduce the extra cost of generating emissions and treating toxics, and increase the total amount of recycling, energy recovery, and compost. Furthermore, such a production unit can be installed and used in a small-scale economic unit (Cipolletta, G., 2021), in an independent residential area, or even in a household, which reduces the impact on the environment.

4.2 Economic Benefits

- Nexus can help identify where possible "tipping points" exist, i.e., where the increases in one benefit relative to another are too extreme. It allows decision-makers and stakeholders to determine what is the best available blend of options (e.g., which WEF Nexus configuration will balance revenue growth in one sector with revenue growth in another), depending on their needs and wishes.
- Reuse waste in a multi-use system to reduce waste/toxic disposal costs; Consider reuse waste in the distributed WEF Nexus system. For example, wastewater is used to irrigate

community farms to save irrigation water costs and reduce household wastewater treatment costs.

- Promote economic development opportunities in low-and middle-income areas and improve employment. SPSS applied to Distributed WEF Nexus is an offering model that is labor and relationship-intensive. It could improve local employment and increase citizens' income. SPSS model usually provides access rights to the WEF Nexus system with small payments, avoiding the initial investment cost. This makes it easier for low-and-middle-income regions to meet social needs with lower costs. Amid COVID-19 pandemic-induced disruptions, sustainable investment funds are on a constant rise, so it is attractive for local stakeholders to enhance services in emerging economies and low-income areas (Sharma et al., 2021b). Increasing services (e.g., renewable energy supply service) in low-income areas will attract more stakeholders and investment, thus contributing to local economic prosperity (Sharma et al., 2021c).

4.3. Social-Ethical Benefits

- Improve the living conditions and employment opportunities of low-and-middle-income groups; The application of Distributed WEF Nexus can increase the return rate of investment, which can bring more development opportunities and more employment to the local area, thus improving the living conditions of low-and-middle-income people.
- Improve the local working condition and promote the dissemination and development of new technologies locally. Advanced technology could increase productivity and improve working conditions. SPSS solutions need the development and support of local skills. It helps the locals introduce advanced technical skills, increase potential employment opportunities, and promote the local dissemination and development of technology.
- Encourage local engagement and improve social cohesion; SPSS helps establish a sustainable WEF Nexus system to share products and services among different users, for example, shared kitchens, micro-grid, shared gardens, etc. This promotes social cohesion, strengthens the mutually beneficial relationship between residents, and impacts local communities' welfare.

4.4 Implementation Limits of SPSS Applied to Distributed WEF Nexus

4.4.1 The Barriers to User Consumption Habits

Consumer behavior is the embodiment of people's options, affected by social norms and the institutional environment. Current consumption habits are the dominant factor hindering the implementation of SPSS applied to Distributed WEF nexus. The SPSS applied to Distributed WEF nexus supplies labor-intensive products, so the price per unit of the WEF supply is on the rise. Consumers will be more inclined to use intuitively cheaper centralized WEF supply (such as electricity from urban power plants, water from water plants, and food from intensive supermarkets). Besides, when purchasing hardware, the product-service system is based on sharing and the right to access. Consumers generally find it challenging to accept solutions without ownership (Ceschin and Gaziulusoy, 2019).

4.4.2 Challenges for Providers and Stakeholders

From companies' or product service providers' perspectives, the lack of infrastructure and technologies involved in disposal and remanufacture hardware/products locally may become a limitation to SPSS construction (Bansal et al., 2020). Besides, the long-term costs of SPSS (such as life cycle costs and benefits) may put pressure on investment. Furthermore, when the supplier/provider owns the product ownership, it is necessary to develop the local functions of SPSS (such as technical and commercial functions) to become a driver to promote local system innovation and diffuse SPSS locally. Meanwhile, the potential cultural barriers may cause user-oriented SPSS and result-oriented SPSS to become barriers to local acceptance of SPSS innovation (Mont, 2001; Ceschin and Gaziulusoy, 2013).

5 CONCLUSION

SPSS and DE models play key roles in designing WEF Nexus solutions towards a service-oriented and result-oriented offering model shifting with the distributed small-scale network. Simultaneously, Distributed WEF Nexus was developed and defined to use the benefits of distributed structure to achieve WEF solutions that are more flexible, near to end-users, customized, and quickly respond to sustainable challenges. We emphasize that viewing water, energy, and food as a nexus system, rather than separately, i.e., as a system to be designed, implemented, and managed, is extremely promising in terms of sustainability and characterizing the SPSS applied to Distributed WEF Nexus has been developed and presented by eleven dimensions canvas, based on the exploration, analysis, and summary of the key issues and features among them. Therefore, 11 dimensions of Canvas were then tested and evaluated for completeness, usability, and effectiveness by inviting multiple companies, experts, and design practitioners. The feedback has been collected after a 1-h test for each expert with the scoring of the questionnaire scale, showing the completeness of the 11 dimensions as an analysis tool at the beginning stage of research that could be used to characterize the main features of the SPSS applied to Distributed WEF Nexus. The majority of respondents gave positive feedback and high scores for its ease of use and ability to facilitate innovation and improvement of ideas according to different dimensions in the strategy analysis and exploration stage of the design process. A more broader using and testing of the 11 dimensions of Canvas tool, including more multi-field experts and practitioners, should also be considered by future studies. All of this will progress further work to explore and develop WEF Nexus-oriented concepts, design strategies, and innovative tools to support companies, practitioners, and designers on how to efficiently build and manage a resilient and sustainable WEF Nexus system to achieve sustainable access to WEF for all.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

ETHICS STATEMENT

Ethical approval/written informed consent was not required for the study of animals/human participants in accordance with the local legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

MG: conceptualization, project administration, methodology, writing—original draft. RH: supervision, funding acquisition, resources, CV: methodology, supervision, validation, writing—review and editing. KM: Supervision, visualization, writing—review and editing. YZ: investigation, resources, visualization.

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REFERENCES

Abulibdeh, A., and Zaidan, E. (2020). Managing the Water-Energy-Food Nexus on an Integrated Geographical Scale. *Environ. Dev.* 33, 100498. doi:10.1016/j.envdev.2020.100498

Al-Sumaiti, A. S., Banhidarah, A. K., Wescoat, J. L., Bamigbade, A. K., and Nguyen, H. t. (2020). Data Collection Surveys on the Cornerstones of the Water-Energy Nexus: a Systematic Overview. *IEEE Access* 8, 93011–93027. doi:10.1109/access.2020.2995054

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 (4), 043002. doi:10.1088/1748-9326/aaa9c6

Allain, S., Ruault, J.-F., Moraine, M., and Madelrieux, S. (2022). The 'bioeconomics vs Bioeconomy' Debate: Beyond Criticism, Advancing Research Fronts. *Environ. Innovation Societal Transitions* 42, 58–73. doi:10.1016/j.eist.2021.11.004

Allan, J. A. (2003). Virtual Water - the Water, Food, and Trade Nexus. Useful Concept or Misleading Metaphor? *Water Int.* 28 (1), 106–113. doi:10.1080/02508060.2003.9724812

Bacchetti, E. (2018). Towards Sustainable Energy for All. Designing Sustainable Product-Service System Applied to Distributed Renewable Energy. Polimi Design PhD_018: 9 PhD theses on design as we do in POLIMI, 120.

Baines, T. S., Lightfoot, H. W., Evans, S., Neely, A., Greenough, R., Peppard, J., et al. (20072003). State-of-the-art in Product-Service Systems. *Proc. Inst. Mech. Eng. B: J. Eng. Manufacture* 221 (10), 1543–1552. doi:10.1243/09544054jem858

Bansal, S., Jain, M., Garg, I., and Srivastava, M. (2020). Attaining Circular Economy through Business Sustainability Approach: An Integrative Review and Research Agenda. *J. Public Aff.*, e2319. doi:10.1002/pa.2319

Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. S. J., and Yumkella, K. K. (2011). Considering the Energy, Water and Food Nexus: Towards an Integrated Modelling Approach. *Energy policy* 39 (12), 7896–7906. doi:10.1016/j.enpol.2011.09.039

Beck, M. B., and Villarroel Walker, R. (2013). On Water Security, Sustainability, and the Water-Food-Energy-Climate Nexus. *Front. Environ. Sci. Eng.* 7 (5), 626–639. doi:10.1007/s11783-013-0548-6

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M. A., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F., Curnow, J., Haworth, B., Duce, S., and Imanari, Y. (2015). Sustainable Development and the Water-Energy-Food Nexus: A Perspective on Livelihoods. *Environ. Sci. Pol.* 54, 389–397. doi:10.1016/j.envsci.2015.08.002

Borowski, P. F. (2021). Innovative Processes in Managing an enterprise from the Energy and Food Sector in the Era of Industry 4.0. *Processes* 9 (2), 381. doi:10.3390/pr9020381

Ceschin, F., and Gaziulusoy, İ. (2019). *Design for Sustainability (Open Access): A Multi-Level Framework from Products to Socio-Technical Systems*. London: Routledge. doi:10.4324/9780429456510

Chai, M., Deng, Y., and Sohail, M. T. (2021). "Study on Synergistic Mechanism of Water Environment Governance in Dongting Lake Basin Based on Evolutionary Game," in E3S Web of Conferences (Xiamen: EDP Sciences). doi:10.1051/e3sconf/202125703075

Chang, Y., Li, G., Yao, Y., Zhang, L., and Yu, C. (2016). Quantifying the Water-Energy-Food Nexus: Current Status and Trends. *Energies* 9 (2), 65. doi:10.3390/en9020065

Cipolletta, G., Ozbayram, E. G., Eusebi, A. L., Akyol, Ç., Malamis, S., Mino, E., et al. (2021). Policy and Legislative Barriers to Close Water-Related Loops in Innovative Small Water and Wastewater Systems in Europe: A Critical Analysis. *J. Clean. Prod.* 288, 125604. doi:10.1016/j.jclepro.2020.125604

Cooper, T., and Evans, S. (2000). *Products to Services. A Report for Friends of the Earth Produced by the Centre for Sustainable Consumption*. UK: Sheffield Hallam University.

Corbin, J., and Strauss, A. (2014). *Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory*. California: Sage Publications.

de Andrade Guerra, J. B. S. O., Berchin, I. I., Garcia, J., da Silva Neiva, S., Jonck, A. V., Faraco, R. A., and Ribeiro, J. M. P. (2020). A Literature-Based Study on the Water–Energy–Food Nexus for Sustainable Development. *Stochastic Environ. Res. Risk Assess.*, 1–22.

Emili, S., Ceschin, F., and Harrison, D. (2016). Product-Service System Applied to Distributed Renewable Energy: A Classification System, 15 Archetypal Models and a Strategic Design Tool. *Energ. Sust. Dev.* 32, 71–98. doi:10.1016/j.esd.2016.03.004

Endo, A., Kumazawa, T., Kimura, M., Yamada, M., Kato, T., and Kozaki, K. (2018). Describing and Visualizing a Water-Energy-Food Nexus System. *Water* 10 (9), 1245. doi:10.3390/w10091245

Endo, A., Tsurita, I., Burnett, K., and Orencio, P. M. (2017). A Review of the Current State of Research on the Water, Energy, and Food Nexus. *J. Hydrol. Reg. Stud.* 11, 20–30. doi:10.1016/j.ejrh.2015.11.010

Food and Agriculture Organization (2020). *International Fund for Agricultural Development*. in *THE STATE OF FOOD SECURITY AND NUTRITION IN THE WORLD 2020*. Rome: United Nations Children's Fund, World Food Programme, & World Health Organization. Available at: http://www.fao.org/3/ca9692en/online/ca9692en.html#.

Food and Agriculture Organization (2021). *Tracking Progress on Food and Agriculture-Related SDG Indicators 2021: A Report on the Indicators under FAO Custodianship*. Rome. doi:10.4060/cb6872en Tracking Progress on Food and Agriculture-Related SDG Indicators 2021: A Report on the Indicators under FAO Custodianship

Gaiardelli, P., Resta, B., Martinez, V., Pinto, R., and Albores, P. (2014). A Classification Model for Product-Service Offerings. *J. Clean. Prod.* 66, 507–519. doi:10.1016/j.jclepro.2013.11.032

Garcia, D. J. (2019). *Life Cycle Optimization of Sustainable Water-Energy-Food Nexus Systems and Networks (PhD Thesis)*. Ann Arbor: Northwestern University.

Garcia, D. J., Lovett, B. M., and You, F. (2019). Considering Agricultural Wastes and Ecosystem Services in Food-Energy-Water-Waste Nexus System Design. *J. Clean. Prod.* 228, 941–955. doi:10.1016/j.jclepro.2019.04.314

Garcia, D. J., and You, F. (2016). The Water-Energy-Food Nexus and Process Systems Engineering: a New Focus. *Comput. Chem. Eng.* 91, 49–67. doi:10.1016/j.compchemeng.2016.03.003

Goedkoop, M. J., Van Halen, C. J., Te Riele, H. R., and Rommens, P. J. (1999). Product Service Systems, Ecological and Economic Basics. *Rep. Dutch Ministries Environ. (Vrom) Econ. Aff. (Ez)* 36 (1), 1–122.

Guta, D., Jara, J., Adhikari, N., Chen, Q., Gaur, V., and Mirzabaev, A. (2017). Assessment of the Successes and Failures of Decentralized Energy Solutions and Implications for the Water-Energy-Food Security Nexus: Case Studies from Developing Countries. *Resources* 6 (3), 24. doi:10.3390/resources6030024

Hoff, J. (2011). "Understanding the Nexus," in Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus, 16–18 November 2011 (Bonn, GermanyStockholm, Sweden: Stockholm Environment Institute (SEI).

Hoolohan, C., Larkin, A., McLachlan, C., Falconer, R., Soutar, I., Suckling, J., Varga, L., Haltas, I., Druckman, A., Lumbroso, D., Scott, M., Gilmour, D., Ledbetter, R., McGrane, S., Mitchell, C., and Yu, D. (2018). Engaging Stakeholders in Research to Address Water-Energy-Food (WEF) Nexus Challenges. *Sustain. Sci.* 13 (5), 1415–1426. doi:10.1007/s11625-018-0552-7

Howells, M., Hermann, S., Welsch, M., Bazilian, M., Segerström, R., Alfstad, T., Gielen, D., Rogner, H., Fischer, G., van Velthuizen, H., Wiberg, D., Young, C., Roehrl, R. A., Mueller, A., Steduto, P., and Ramma, I. (2013). Integrated Analysis of Climate Change, Land-Use, Energy and Water Strategies. *Nat. Clim Change* 3 (7), 621–626. doi:10.1038/nclimate1789

International Energy Agency (2020). *SDG7: Data and Projections Access to Affordable, Reliable, Sustainable and Modern Energy for All*. Available at: https://www.iea.org/reports/sdg7-data-and-projections.

International Institute for Industrial Environmental Economics (2009). *The Future Is Distributed: A Vision of Sustainable Economies*. Lund: IIIEE, Lund University.

International Institute for Sustainable Development (2013). The Water–Energy–Food Security Nexus: Towards a Practical Planning and Decision-Support Framework for Landscape Investment and Risk Management. Available at: https://www.iisd.org/system/files/publications/wef_nexus_2013.pdf.

Jain, M., Sharma, G. D., Goyal, M., Kaushal, R., and Sethi, M. (2021). Econometric Analysis of COVID-19 Cases, Deaths, and Meteorological Factors in South Asia. *Environ. Sci. Pollut. Res.* 28 (22), 28518–28534. doi:10.1007/s11356-021-12613-6

Jiang, A., Cao, Y., Sohail, M. T., Majeed, M. T., and Sohail, S. (2021). Management of green Economy in China and India: Dynamics of Poverty and Policy Drivers. *Environ. Sci. Pollut. Res.* 28 (39), 55526–55534. doi:10.1007/s11356-021-14753-1

Johansson, A., Kisch, P., and Mirata, M. (2005). Distributed economies - A new engine for innovation. *J. Clean. Prod.* 13 (10-11), 971–979. doi:10.1016/j.jclepro.2004.12.015, 971–979. doi:10.1016/j.jclepro.2004.12.015 Distributed Economies–A New Engine for Innovation*J. Clean. Prod.*10-11

Karabulut, A., Egoh, B. N., Lanzanova, D., Grizzetti, B., Bidoglio, G., Pagliero, L., Bouraoui, F., Aloe, A., Reynaud, A., Maes, J., Vandecasteele, I., and Mubareka, S. (2016). Mapping Water Provisioning Services to Support the Ecosystem-Water-Food-Energy Nexus in the Danube River basin. *Ecosystem Serv.* 17, 278–292. doi:10.1016/j.ecoser.2015.08.002

Keairns, D. L., Darton, R. C., and Irabien, A. (2016). The Energy-Water-Food Nexus. *Annu. Rev. Chem. Biomol. Eng.* 7, 239–262. doi:10.1146/annurev-chembioeng-080615-033539

Kohtala, C. (2015). Addressing Sustainability in Research on Distributed Production: an Integrated Literature Review. *J. Clean. Prod.* 106, 654–668. doi:10.1016/j.jclepro.2014.09.039

Kölbel, J., Strong, C., Noe, C., and Reig, P. (2018). *Mapping Public Water Management by Harmonizing and Sharing Corporate Water Risk Information*. Washington, DC: World Resources Institute. Available at: www.wri.org/publication/mapping-public-water.

Küblböck, K., Omann, I., Grohs, H., Karutz, R., Klassert, C., Klauer, B., and Gorelick, S. (2021). *The Role of Sustainability Living Labs in Understanding Food-Water-Energy Nexus Challenges and Solutions in India and Jordan (No. 63)*. Vienna: ÖFSE Working Paper.

Kurian, M. (2017). The Water-Energy-Food Nexus. *Environ. Sci. Pol.* 68, 97–106. doi:10.1016/j.envsci.2016.11.006

Lan, H., Cheng, C., and Sohail, M. T. (2021). *Asymmetric Determinants of CO2 Emissions in China: Do Government Size and Country Size Matter?*

Lawford, R., Bogardi, J., Marx, S., Jain, S., Wostl, C. P., Knüppe, K., Ringler, C., Lansigan, F., and Meza, F. (2013). Basin Perspectives on the Water-Energy-Food Security Nexus. *Curr. Opin. Environ. Sustainability* 5 (6), 607–616. doi:10.1016/j.cosust.2013.11.005

Leck, H., Conway, D., Bradshaw, M., and Rees, J. (2015). Tracing the Water-Energy-Food Nexus: Description, Theory and Practice. *Geogr. Compass* 9 (8), 445–460. doi:10.1111/gec3.12222

Levinson, A., Rosenberg, C., and Yansane, A. (1977). "The Political Economy of Energy and Agriculture in the Third World A. Levinson and C. Rosenberg Are Doctoral Candidates in the Dept. Of Agricultural and Resource Economics, and A. Yansane Is Assistant Professor, Afro-American Studies. University of California, Berkeley, Calif. 94720," in *Agriculture and Energy* (Academic Press), 639–655. doi:10.1016/b978-0-12-454250-1.50051-4

Liu, J., Yang, H., Cudennec, C., Gain, A. K., Hoff, H., Lawford, R., Qi, J., Strasser, L. d., Yillia, P. T., and Zheng, C. (2017). Challenges in Operationalizing the Water-Energy-Food Nexus. *Hydrological Sci. J.* 62 (11), 1714–1720. doi:10.1080/02626667.2017.1353695

Liu, N., Hong, C., and Sohail, M. T. (2021). Does Financial Inclusion and Education Limit CO2 Emissions in China? A New Perspective. *Environ. Sci. Pollut. Res.* 29 (13), 18452–18459. doi:10.1007/s11356-021-17032-1

Liu, Y., Sohail, M. T., Khan, A., and Majeed, M. T. (2021). Environmental Benefit of Clean Energy Consumption: Can BRICS Economies Achieve Environmental Sustainability through Human Capital? *Environ. Sci. Pollut. Res.* 29, 1–11. doi:10.1007/s11356-021-16167-5

Mabrey, D., and Vittorio, M. (2018). Moving from Theory to Practice in the Water–Energy–Food Nexus: an Evaluation of Existing Models and Frameworks. *Water-Energy Nexus* 1 (1), 17–25. doi:10.1016/j.wen.2018.04.001

Mahfooz, Y., Yasar, A., Bari Tabinda, A., Sohail, M. T., Siddiqua, A., and Mahmood, S. (2017). Quantification of the River Ravi Pollution Load and Oxidation Pond Treatment to Improve the drain Water Quality. *Dwt* 85, 132–137. doi:10.5004/dwt.2017.21195

Mahfooz, Y., Yasar, A., Sohail, M. T., Tabinda, A. B., Rasheed, R., Irshad, S., et al. (2019). Investigating the Drinking and Surface Water Quality and Associated Health Risks in a Semi-arid Multi-Industrial metropolis (Faisalabad), Pakistan. *Environ. Sci. Pollut. Res.* 26 (20), 20853–20865. doi:10.1007/s11356-019-05367-9

Manzini, E., and Vezzoli, C. (2003). A Strategic Design Approach to Develop Sustainable Product Service Systems: Examples Taken from the 'environmentally Friendly Innovation' Italian Prize. *J. Clean. Prod.* 11 (8), 851–857. doi:10.1016/s0959-6526(02)00153-1

Meadows, D. H., Meadows, D. L., Randers, J., and Behrens, W. W. (1972). *The Limits to Growth*, 102. New York, 27.

Melloni, G., Turetta, A., Bonatti, M., and Sieber, S. (2020). A Stakeholder Analysis for a Water-Energy-Food Nexus Evaluation in an Atlantic Forest Area: Implications for an Integrated Assessment and a Participatory Approach. *Water* 12 (7), 1977. doi:10.3390/w12071977

Mercure, J.-F., Paim, M. A., Bocquillon, P., Lindner, S., Salas, P., Martinelli, P., Berchin, I. I., de Andrade Guerra, J. B. S. O., Derani, C., de Albuquerque Junior, C. L., Ribeiro, J. M. P., Knobloch, F., Pollitt, H., Edwards, N. R., Holden, P. B., Foley, A., Schaphoff, S., Faraco, R. A., and Vinuales, J. E. (2019). System Complexity and Policy Integration Challenges: The Brazilian Energy- Water-Food Nexus. *Renew. Sust. Energ. Rev.* 105, 230–243. doi:10.1016/j.rser.2019.01.045

Meredith, J. (1993). Theory Building through Conceptual Methods. *Int. J. Operations Prod. Manag.* 13 (5), 3–11. doi:10.1108/01443579310028120

Mont, O. (2001). Introducing and Developing a Product-Service System (PSS) Concept in Sweden, IIIEE Reports 2001:6. Lund: IIIEE, Lund University and NUTEK. United Nations Environmental Programme (UNEP). Product–service systems and sustainability. Opportunities for sustainable solutions. Paris: UNEP, Division of Technology Industry and Economics, Production and Consumption Branch; 2002

Muhammad, A. M., Zhonghua, T., Dawood, A. S., and Sohail, M. T. (2014). A Study to Investigate and Compare Groundwater Quality in Adjacent Areas of Landfill Sites in Lahore City. *Nat. Environ. Pollut. Tech.* 13 (1).

Naidoo, D., Nhamo, L., Mpandeli, S., Sobratee, N., Senzanje, A., Liphadzi, S., Slotow, R., Jacobson, M., Modi, A. T., and Mabhaudhi, T. (2021). Operationalising the Water-Energy-Food Nexus through the Theory of Change. *Renew. Sustain. Energ. Rev.* 149, 111416. doi:10.1016/j.rser.2021.111416

Namany, S., Al-Ansari, T., and Govindan, R. (2019). Sustainable Energy, Water and Food Nexus Systems: a Focused Review of Decision-Making Tools for Efficient Resource Management and Governance. *J. Clean. Prod.* 225, 610–626. doi:10.1016/j.jclepro.2019.03.304

Nasrullah, M., Rizwanullah, M., Yu, X., Jo, H., Sohail, M. T., and Liang, L. (2021). Autoregressive Distributed Lag (ARDL) Approach to Study the Impact of Climate Change and Other Factors on rice Production in South Korea. *J. Water Clim. Change* 12 (6), 2256–2270. doi:10.2166/wcc.2021.030

Nicola, M., Alsafi, Z., Sohrabi, C., Kerwan, A., Al-Jabir, A., Iosifidis, C., Agha, M., and Agha, R. (2020). The Socio-Economic Implications of the Coronavirus Pandemic (COVID-19): A Review. *Int. J. Surg.* 78, 185–193. doi:10.1016/j.ijsu.2020.04.018

Obersteiner, M., Walsh, B., Frank, S., Havlík, P., Cantele, M., Liu, J., et al. (2016). Assessing the Land Resource-Food price Nexus of the Sustainable Development Goals. *Sci. Adv.* 2 9, e1501499. doi:10.1126/sciadv.1501499

Petrulaityte, A., Ceschin, F., Pei, E., and Harrison, D. (2017). Supporting Sustainable Product-Service System Implementation through Distributed Manufacturing. *Proced. CIRP* 64, 375–380. doi:10.1016/j.procir.2017.03.070

Putra, M. P. I. F., Pradhan, P., and Kropp, J. P. (2020). A Systematic Analysis of Water-Energy-Food Security Nexus: A South Asian Case Study. *Sci. Total Environ.* 728, 138451. doi:10.1016/j.scitotenv.2020.138451

Qadir, M., Sharma, B. R., Bruggeman, A., Choukr-Allah, R., and Karajeh, F. (2007). Non-conventional Water Resources and Opportunities for Water Augmentation to Achieve Food Security in Water Scarce Countries. *Agric. Water Manag.* 87 (1), 2–22. doi:10.1016/j.agwat.2006.03.018

Radini, S., Marinelli, E., Akyol, Ç., Eusebi, A. L., Vasilaki, V., Mancini, A., Frontoni, E., Bischetti, G. B., Gandolfi, C., Katsou, E., and Fatone, F. (2021). Urban Water-Energy-Food-Climate Nexus in Integrated Wastewater and Reuse Systems: Cyber-Physical Framework and Innovations. *Appl. Energ.* 298, 117268. doi:10.1016/j.apenergy.2021.117268

Rasool, A., Jundong, H., and Sohail, M. T. (2017). Relationship of Intrinsic and Extrinsic Rewards on Job Motivation and Job Satisfaction of Expatriates in China. *J. Appl. Sci.* 17 (3), 116–125. doi:10.3923/jas.2017.116.125

Reigado, C. R., Fernandes, S. d. C., Saavedra, Y. M. B., Ometto, A. R., and Costa, J. M. H. d. (2017). A Circular Economy Toolkit as an Alternative to Improve the Application of PSS Methodologies. *Proced. CIRP* 64, 37–42. doi:10.1016/j.procir.2017.03.034

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. Sustainability* 5 (6), 617–624. doi:10.1016/j.cosust.2013.11.002

Santos Da Silva, S. R., Miralles-Wilhelm, F., Muñoz-Castillo, R., Clarke, L. E., Braun, C. J., Delgado, A., et al. (2019). The Paris Pledges and the Energy-Water-Land Nexus in Latin America: Exploring Implications of Greenhouse Gas Emission Reductions. *PloS one* 14 (4), e0215013. doi:10.1371/journal.pone.0215013

Shahab, A., Shihua, Q., Rashid, A., Hasan, F. U., and Sohail, M. T. (2016). Evaluation of Water Quality for Drinking and Agricultural Suitability in the Lower Indus Plain in Sindh Province, Pakistan. *Polish J. Environ. Stud.* 25 (6). doi:10.15244/pjoes/63777

Sharma, G. D., Bansal, S., Yadav, A., Jain, M., and Garg, I. (2021). Meteorological Factors, COVID-19 Cases, and Deaths in Top 10 Most Affected Countries: an Econometric Investigation. *Environ. Sci. Pollut. Res.* 28 (22), 28624–28639. doi:10.1007/s11356-021-12668-5

Sharma, G. D., Rahman, M. M., Jain, M., and Chopra, R. (2021c). Nexus between Energy Consumption, Information and Communications Technology, and Economic Growth: an Enquiry into Emerging Asian Countries. *J. Public Aff.* 21 (2), e2172. doi:10.1002/pa.2172

Sharma, G. D., Tiwari, A. K., Jain, M., Yadav, A., and Srivastava, M. (2021a). COVID-19 and Environmental Concerns: A Rapid Review. *Renew. Sust. Energ. Rev.* 148, 111239. doi:10.1016/j.rser.2021.111239

Sharma, G. D., Tiwari, A. K., Talan, G., and Jain, M. (2021b). Revisiting the Sustainable versus Conventional Investment Dilemma in COVID-19 Times. *Energy Policy* 156, 112467. doi:10.1016/j.enpol.2021.112467

Simpson, G. B., and Jewitt, G. P. W. (2019). The Development of the Water-Energy-Food Nexus as a Framework for Achieving Resource Security: A Review. *Front. Environ. Sci.* 7, 8. doi:10.3389/fenvs.2019.00008

Sohail, M., Delin, H., and Siddiq, A. (2014). Indus basin Waters a Main Resource of Water in Pakistan: an Analytical Approach. *Curr. World Environ.* 9 (3), 670–685. doi:10.12944/cwe.9.3.16

Sohail, M. T., Ullah, S., Majeed, M. T., Usman, A., and Andlib, Z. (2021b). The Shadow Economy in South Asia: Dynamic Effects on Clean Energy Consumption and Environmental Pollution. *Environ. Sci. Pollut. Res. Int.* 28 (23), 29265–29275. doi:10.1007/s11356-021-12690-7

Sohail, M. T., Xiuyuan, Y., Usman, A., Majeed, M. T., and Ullah, S. (2021). Renewable Energy and Non-renewable Energy Consumption: Assessing the Asymmetric Role of Monetary Policy Uncertainty in Energy Consumption. *Environ. Sci. Pollut. Res. Int.* 28 (24), 31575–31584. doi:10.1007/s11356-021-12867-0

Sohail, M. T., Aftab, R., Mahfooz, Y., Yasar, A., Yen, Y., Shaikh, S. A., et al. (2019a). Estimation of Water Quality, Management and Risk Assessment in Khyber-Pakhtunkhwa and Gilgit Baltistan Pakistan. *Dwt* 171, 105–114. doi:10.5004/dwt.2019.24925

Sohail, M. T., Delin, H., Siddiq, A., Idrees, F., and Arshad, S. (2015). Evaluation of Historic Indo-Pak Relations, Water Resource Issues and its Impact on Contemporary Bilateral Affairs. *Asia Pac. J. Multidisciplinary Res.* 3 (1).

Sohail, M. T., Huang, D., Bailey, E., Akhtar, M. M., and Talib, M. A. (2013). Regulatory Framework of mineral Resources Sector in Pakistan and Investment Proposal to Chinese Companies in Pakistan. *Ajibm* 03 (05), 514–524. doi:10.4236/ajibm.2013.35059

Sohail, M. T., Mahfooz, Y., Azam, K., Yat, Y., Genfu, L., and Fahad, S. (2019). Impacts of Urbanization and Land Cover Dynamics on Underground Water in Islamabad, Pakistan. *Dwt* 159, 402–411. doi:10.5004/dwt.2019.24156

Sohail, M. T., Majeed, M. T., Shaikh, P. A., and Andlib, Z. (2021c). Environmental Costs of Political Instability in Pakistan: Policy Options for Clean Energy Consumption and Environment. *Environ. Sci. Pollut. Res.*, 1–10. doi:10.1007/s11356-021-17646-5

Sohail, M. T., Ullah, S., Majeed, M. T., and Usman, A. (2021a). Pakistan Management of green Transportation and Environmental Pollution: a Nonlinear ARDL Analysis. *Environ. Sci. Pollut. Res.* 28 (23), 29046–29055. doi:10.1007/s11356-021-12654-x

Stein, C., Barron, J., Nigussie, L., Gedif, B., Amsalu, T., and Langan, S. J. (2014). *Advancing the Water-Energy-Food Nexus: Social Networks and Institutional Interplay in the Blue Nile.*

Stein, C., Pahl-Wostl, C., and Barron, J. (2018). Towards a Relational Understanding of the Water-Energy-Food Nexus: an Analysis of Embeddedness and Governance in the Upper Blue Nile Region of Ethiopia. *Environ. Sci. Pol.* 90, 173–182. doi:10.1016/j.envsci.2018.01.018

Tayyab Sohail, M., Delin, H., Afnan Talib, M., Xiaoqing, X., and Muhammad Akhtar, M. (2014a). An Analysis of Environmental Law in Pakistan-policy and Conditions of Implementation. *Rjaset* 8 (5), 644–653. doi:10.19026/rjaset.8.1017

Tayyab Sohail, M., Lin, X., Lizhi, L., Rizwanullah, M., Nasrullah, M., Xiuyuan, Y., Manzoor, Z., and Elis, R. (2021d). Farmers' Awareness about Impacts of Reusing Wastewater, Risk Perception and Adaptation to Climate Change in Faisalabad District, Pakistan. *Pol. J. Environ. Stud.* 30, 4663–4675. doi:10.15244/pjoes/134292

Terrapon-Pfaff, J., Ortiz, W., Dienst, C., and Gröne, M.-C. (2018). Energising the WEF Nexus to Enhance Sustainable Development at Local Level. *J. Environ. Manage.* 223, 409–416. doi:10.1016/j.jenvman.2018.06.037

Tukker, A. (2004). Eight Types of Product-Service System: Eight Ways to Sustainability? Experiences from SusProNet. *Bus. Strat. Env.* 13 (4), 246–260. doi:10.1002/bse.414
Tukker, A., and Tischner, U. (2006). *New Business for Old Europe: Product-Service Development*. Sheffield: Competitiveness and SustainabilityGreenleaf.
United Nations Environmental Programme (UNEP) (2002). *Product-service Systems and Sustainability. Opportunities for Sustainable Solutions*. Paris, France: UNEP, Division of Technology Industry and Economics, Production and Consumption Branch.
United Nations Department of Economic and Social Affairs (2019). *World Population Prospects 2019: Highlights*. Retrieved from https://population.un.org/wpp/Publications/Files/WPP2019_10KeyFindings.pdf.
US Energy Information Administration (2020). *US Energy Information Administration's International Energy Outlook 2020 (IEO2020)*. Available at: https://www.eia.gov/outlooks/ieo/pdf/ieo2020.pdf.
Vezzoli, C., Ceschin, F., Diehl, J. C., and Kohtala, C. (2015). "New Design Challenges to Widely Implement 'Sustainable Product-Service Systems'," in *Journal of Cleaner Production, Volume 97, Special Volume Why Have "Sustainable Product-Service Systems" Not Been Widely Implemented, Guest*. Editors C. Vezzoli, F. Ceschin, J. C. Diehl, and C. Kohtala, 97, 1–12. doi:10.1016/j.jclepro.2015.02.061
Vezzoli, C., Ceschin, F., Osanjo, L., M'Rithaa, M. K., Moalosi, R., Nakazibwe, V., et al. (2018). Designing Sustainable Energy for All, *Sustainable Product-Service System Design Applied to Distributed Renewable Energy*. London: Springer, 1–202. 978-3-319-70223-0. doi:10.1007/978-3-319-70223-0
Vezzoli, C., Delfino, E., and Ambole, L. A. (2014). System Design for Sustainable Energy for All. A New Challenging Role for Design to foster Sustainable Development. *FORMakademisk* 7 (3), 1–27. doi:10.7577/formakademisk.791
Vezzoli, C., Kohtala, C., Srinivasan, A., Xin, L., Fusakul, M., Sateesh, D., et al. (2017). *Product-service System Design for Sustainability*. London: Routledge.
Wacker, J. G. (1998). A Definition of Theory: Research Guidelines for Different Theory-Building Research Methods in Operations Management. *J. operations Manag.* 16 (4), 361–385. doi:10.1016/s0272-6963(98)00019-9
Weitz, N., Strambo, C., Kemp-Benedict, E., and Nilsson, M. (2017). Closing the Governance Gaps in the Water-Energy-Food Nexus: Insights from Integrative Governance. *Glob. Environ. Change* 45, 165–173. doi:10.1016/j.gloenvcha.2017.06.006
World Economic Forum (2011). *Global Risks 2011 Report*. 6th edition. Available at: https://www.weforum.org/reports/global-risks-report-2011.
World Health Organization & The United Nations Children's Fund (2019). June 18). Available at: www.who.int website https://www.who.int/news/item/18-06-2019-1-in-3-people-globally-do-not-have-access-to-safe-drinking-water-unicef-who.
Yen, Y., Wang, Z., Shi, Y., Xu, F., Soeung, B., Sohail, M. T., Rubakula, G., and Juma, S. A. (2017). The Predictors of the Behavioral Intention to the Use of Urban green Spaces: The Perspectives of Young Residents in Phnom Penh, Cambodia. *Habitat Int.* 64, 98–108. doi:10.1016/j.habitatint.2017.04.009
Yi, J., Guo, J., Ou, M., Pueppke, S. G., Ou, W., Tao, Y., et al. (2020). Sustainability Assessment of the Water-Energy-Food Nexus in Jiangsu Province, China. *Habitat Int.* 95, 102094. doi:10.1016/j.habitatint.2019.102094
Zhao, P., Yen, Y., Bailey, E., and Sohail, M. (2019). Analysis of Urban Drivable and Walkable Street Networks of the ASEAN Smart Cities Network. *Ijgi* 8 (10), 459. doi:10.3390/ijgi8100459

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