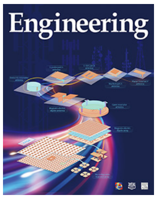
Engineering 11 (2022) 95–100

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng



Research
Environmental Sustainability—Perspective

Creating a Research Enterprise Framework for Transdisciplinary Networking to Address the Food–Energy–Water Nexus

Jie Zhuang [a,b,c,*], Frank E. Löffler [a,b,d,e,f], Gary S. Sayler [a,b,d]

[a] Department of Biosystems Engineering and Soil Science, The University of Tennessee, Knoxville, TN 37996, USA
[b] Center for Environmental Biotechnology, The University of Tennessee, Knoxville, TN 37996, USA
[c] Institute for a Secure and Sustainable Environment, The University of Tennessee, Knoxville, TN 37996, USA
[d] Department of Microbiology, The University of Tennessee, Knoxville, TN 37996, USA
[e] Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville, TN 37996, USA
[f] Biosciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA

ARTICLE INFO

Article history:
Received 23 January 2021
Revised 7 July 2021
Accepted 10 August 2021
Available online 22 October 2021

Keywords:
Food
Energy
Water
Stakeholder
Policy
Environmental sustainability

ABSTRACT

Urbanization, population growth, and the accelerating consumption of food, energy, and water (FEW) resources bring unprecedented challenges for economic, environmental, and social (EES) sustainability. It is imperative to understand the potential impacts of FEW systems on the realization of the United Nation's Sustainable Development Goals (SDGs) as the world transitions from natural ecosystems to managed ecosystems at an accelerating rate. A major obstacle is the complexity and emergent behavior of FEW systems and associated networks, for which no single discipline can generate a holistic understanding or meaningful projections. We propose a research enterprise framework for promoting transdisciplinarity and top-down quantification of the interrelationships between FEW and EES systems. Relevant enterprise efforts would emphasize increasing FEW resource accessibility by improving coordinated interplays across sectors and scales, expanding and diversifying supply-chain networks, and innovating technologies for efficient resource utilization. This framework can guide the development of strategic solutions for diminishing the competition among FEW-consuming sectors in a region or country, and for minimizing existing inequalities in FEW availability when a sustainable development agenda is implemented.

1. Introduction

Communicating issues and trends that are driven by climate change and population dynamics—particularly those that directly influence global sustainability from an environmental and socioeconomic perspective—is one of the primary goals of the United Nation's Sustainable Development Goals (SDGs) [1,2]. The effectiveness of such communication relies on robust transdisciplinary research-coordination networks [3,4]. A few excellent frameworks have been proposed to facilitate the development of conceptual guidance, and analytical tools for assessing the food, energy, and water (FEW) nexus have been developed [5–8]. These approaches are mostly based on a bottom-up approach (i.e., from result to mechanism) because the effects of economic, environmental, and social (EES) issues have not been sufficiently or explicitly defined. Although the bottom-up approach is very important, a top-down approach (i.e., from mechanism to result) to the FEW nexus is also very necessary for developing a transdisciplinary research-coordination network that can effectively facilitate "win–win" interactions between EES and FEW systems. Top-down thinking can facilitate interconnected research opportunities from local to global scales that will ensure FEW sustainability under increasing climate-change stress and the pressures from a burgeoning human population [9].

At the global scale, the initial focus of such transdisciplinary networks should fall on the countries that exert large influences on the global FEW systems (e.g., the United States and China) and have disparities in FEW practices, needs, and challenges [10]. These countries are in a unique position to engage in problem definition and solutions through transdisciplinary dialogue among

---

* Corresponding author.
E-mail address: jzhuang@utk.edu (J. Zhuang).

https://doi.org/10.1016/j.eng.2021.08.017

themselves as well as with other countries. For example, countries with comparably low population densities but high FEW resource capacities (e.g., the United States and Australia) not only embrace but also pioneer the application of emerging technologies (e.g., artificial intelligence) for maximizing the efficiency of food production and minimizing associated environmental footprints [11,12]. These activities can potentially deliver universal solutions for the preservation of FEW resources at local to regional scales. In contrast, many other countries with high population density but limited FEW resources (e.g., China and India) still struggle to establish FEW security and face increasing FEW conflicts [13]. Such unequal distributions of the supply and consumption of FEW resources among regions and countries can eventually destabilize the global FEW systems and render at least some of the United Nation's SDGs unachievable.

To reduce the inequities of FEW production and consumption among regions and countries, a scalable transdisciplinary network can facilitate the evaluation, coordination, and balancing of positive and negative impacts of FEW supply chains. Such a network, if robust, should play key roles in identifying risks, recommending solutions, and educating stakeholders regarding the long-term impacts of international FEW exchanges on the EES sustainability of the involved regions and countries. This predictive capability of the new framework is mostly due to two advantages of transdisciplinary approaches. First, transdisciplinarity breaks the boundaries between disciplines and enables top-down views on disorderly problems. Such an approach facilitates the systematic identification of threshold barriers for conflicts (e.g., urbanization vs ecosystem restoration, food demand vs water resources, and energy supply vs social welfare). Second, the approach connects or merges isolated theories and technologies to develop transdisciplinary, innovative solutions. These solutions can solve multiple problems at the same time by strengthening the mechanistic interactions among different systems (e.g., agro-wastes used for energy production or nutrient-rich water used for crop irrigation). Unfortunately, there has not been a framework that can guide the development of such a transdisciplinary network. The lack of such a framework precludes an understanding of the embedded relationships between FEW and EES systems—not to mention their dynamic feedback effects when any new practices are applied to a sub-system. Therefore, this perspective proposes an enterprise framework that treats FEW research as a joint business of researchers, stakeholders (including policymakers), and the public, who represent a broad spectrum of EES communities.

2. Transdisciplinary networking for nexus research

2.1. A research enterprise framework

Transdisciplinary research efforts should clearly identify the system under study and explore what current models (if any) have been developed and implemented to describe that system at local, regional, and global scales [14]. The components and potential interactions of FEW systems should be identified in a broader context (e.g., involving socioeconomic systems), and a framework for inspired fundamental research aimed at solving real-world problems must emerge [15]. For example, how do system-level research questions provide avenues for investigation by individual researchers? How does such research contribute to a broad collective vision for, and understanding of, the FEW nexus? And how do the proposed science and technology efforts converge to provide the research community and stakeholders with a more complete understanding of the problems, potential solutions, and new technical approaches for implementation at various scales and in various contexts? To answer these questions, we need a network perspective that can visualize and prioritize relevant FEW interrelationships from production to consumption. Seven guiding questions to help nexus modeling [15] are very useful in developing customized models to analyze various FEW scenarios according to the needs and interests of stakeholders. A tradeoff analysis relies on a complete or balanced understanding of an entire system [5]. Therefore, in this study, we examine the FEW nexus from the perspective of research enterprise. The term "research enterprise" refers to a large, coordinated effort toward the transdisciplinary integration of research activities into a centralized business model that involves stakeholders, policymakers, and non-research organizations. Fig. 1 shows a complex system network that highlights critical environmental influences on the individual components of FEW systems, feedbacks that affect the environment, and consequences for social (i.e., human) behavior, policy, and technology. These components are inexorably linked to global drivers of

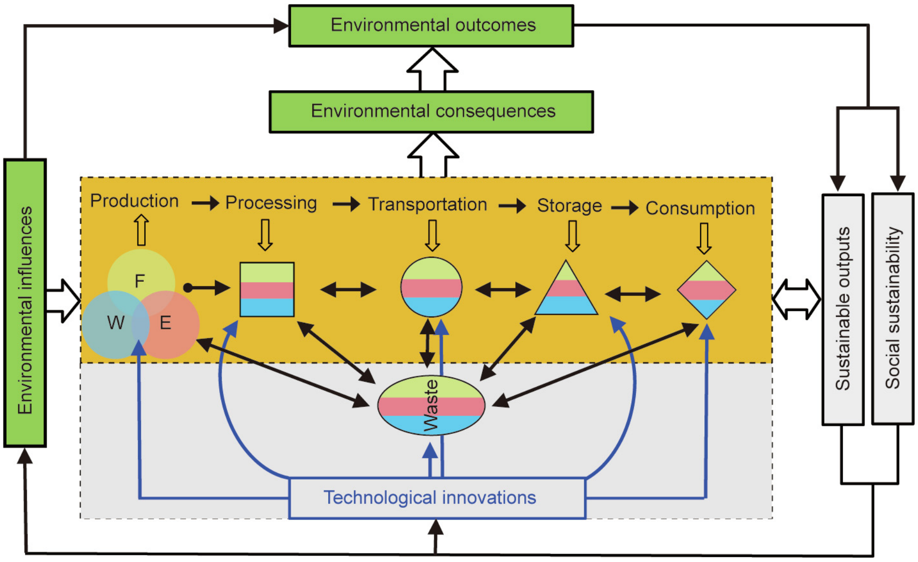


Fig. 1. A research enterprise framework for prioritizing FEW interactions with environmental (green), economic (yellow), and societal (grey) systems. The vectors represent quantifiable material, information, and energy flows. The three-color shapes in the economic system illustrate a difference in the FEW nexus associated with each stage of the supply chain. F: food; W: water; E: energy.

ecosystem change (e.g., greenhouse gas emissions) [16] and to the burgeoning global human population (i.e., an increase of about two billion by 2050) [17]. The framework depicted in Fig. 1 and detailed below anticipates the emergence of unforeseen properties and events that require a global research enterprise endeavor. Such an endeavor would aim to understand the implications of the FEW nexus for sustainable development; its focus would be on the development of systematic modeling and computation technologies, based on diverse inputs from experimentalists, technologists, and behavioral scientists.

2.2. The economic system

The FEW nexus is embedded into the economic system from production to processing, transportation, storage, and consumption. Production is not limited to food; in fact, it represents all FEW elements. Approximately 30% of energy and 70% of freshwater are used for food production; at least 40% of energy is consumed for water extraction, delivery, and treatment; and 25%–45% of water is used for energy generation [1,9]. In this context, the element of food is largely representative of commodity agriculture, livestock production, dairy farming, ground-cover cultivation, and aquaculture and fisheries, among others, whether used for human or nonhuman consumption. Indeed, food is not strictly limited to edible sources of biomass. It includes the biomass used in energy production and the bio-feedstocks used to produce commodity chemicals [4]. Energy production includes fossil and nuclear energy, renewable energy, and energy captured from waste streams, as well as from human and animal labor. Each of these energy sources carries its own cost burden for production in terms of energy and water consumption. The FEW element of water is representative of all sources of water, including surface water, groundwater, soil water, reclaimed water, saline water, and wastewater generated during food and energy production. The sources and uses of these waters may be connected, and balanced approaches are paramount, depending on local, regional, and national needs [18].

The processing of foods and the associated water consumption take many forms, ranging from produce washing to the more complicated processes of milling, brewing, baking, and slaughtering. Processing can occur onsite or offsite (e.g., in the home) and may incur energy costs. Virtually all energy sources, including electricity, require some degree of processing, which may involve step-up and step-down transformers, rectifiers for photovoltaics, petroleum refining, and gas purification. Energy processing can be local or distant. Water sources, depending on the end use, generally require processing to reach usage-specific quality standards. For example, semiconductor manufacturers and chocolate-confectionary industries require particle-free or sterile process water. Notable exceptions are water sources for irrigation and livestock production, which are often unregulated and are therefore of variable—and often poor—quality.

The storage of raw products on a large scale and for the long term to match the temporally and spatially uneven distribution of demand and supply often requires humidity control and fumigation to protect product quality [19]. The onsite ensilage of raw commodities (e.g., grains) or processed materials and cold or frozen storage at distribution centers are commonly practiced. Atmospheric control is employed for long-term storage and for the targeted ripening of fruits and vegetables. Short-term retail storage is common and may involve the use of additives (e.g., antioxidants and ripening agents). Consumer storage can range from as little as a few hours to weeks and months, depending on available refrigeration and food type.

Transportation involves all stages of the supply chains of FEW products. It is estimated that foods in the United States travel approximately 2400 km to get from farm to plate (i.e., 1500 food miles). This long-distance transportation leads to the consumption of about 10 kcal of fossil fuel energy per 1 kcal of food energy (1 kcal = 4.184×10^3 J) [20]. Therefore, shortening food miles by increasing the locally sourced food supply is becoming important for carbon footprint reduction of the food system. In 2020, about 26% of all US energy consumption was spent on transporting people and goods, with petroleum accounting for about 90% of the total US transportation-sector energy use [21]. Such a heavy dependence on a fossil fuel substantially increases greenhouse gas emissions—a concern that drives the development and adoption of environmentally friendly modes of transportation. For example, 90% of all international trade in 2020 was accomplished by water transportation, which generates about 50 times less carbon dioxide (CO_2) than air freight. In recent years, the demand for electric vehicles has rapidly increased, as more and more countries set more stringent air quality standards and reduce CO_2 emissions. However, the rapid development of the electric vehicle market will likely impact FEW supply chains in the near future.

Consumption—by both humans and animals—represents the end use of FEW products. Consumption by animals includes livestock, poultry, aquaculture feeds, and pet foods. Consumption of FEW products also includes such competing nonhuman demands as industrial feedstock and biofuels. Notably, of all the food produced for human consumption in industrialized countries (e.g., the United States), only about two-thirds is actually consumed, while the remainder is wasted [22]. Consumption has large footprints on FEW flows, and is a major force driving the imbalance of EES development at the regional and global levels [4,23]. For example, regional trade within Asia–Pacific countries enlarged the economic and environmental inequity in the region during the period from 1995 to 2015 [23]. Higher income countries gained economic benefits while shifting their environmental burdens (e.g., water consumption) to lower income countries.

2.3. The environmental system

The FEW nexus has strong feedback interactions with environmental systems in terms of influence, consequences, and outcomes. Major environmental influences are caused by population growth and climate change. For example, population growth places severe stress on the security and sustainability of FEW systems and creates the need to bring more marginal lands into arable production [24]. This stress is amplified by the longitudinal effects of increases in global temperature and in the frequency of extreme climatic events [13]. These influences are altering ecological processes, functions, and mechanisms (e.g., the extent and range of plant and animal pests, noxious and toxic plant species, and disease agents) [25,26]. In response, farmers increase nutrient amendments, pesticide applications, and the use of antibiotics and hormones to maintain agricultural productivity and profitability. Unfortunately, these agrochemicals cause unintended impairments of animal and plant communities and soil health and fertility. These actions may result in a series of environmental consequences, such as diminishing the capacity of FEW systems to provide goods and services, degrading water quality, and increasing the release of greenhouse gases (e.g., methane and nitrous oxide). These consequences create feedback influences that accelerate warming and water scarcity. As scientific knowledge about these feedback loops is still emerging, the interactions between FEW and environmental systems cannot be predicted and are unlikely to be understood by policymakers, while being difficult to communicate to primary stakeholders, producers, and the public. These uncertainties are triggering a variety of environmental outcomes, including socioeconomic changes, altered land-use patterns, and intensified exploitation of FEW resources (e.g., through urban agriculture) [7]. However, the extent of these changes depends on difficult-to-predict socioeconomic factors [27,33], such as consumers' adaptive behaviors and changes in FEW consumption choices [25,28].

2.4. The societal system

Societal behaviors have a strong impact on the FEW nexus and influence waste management, technological innovation, sustainable outputs, and social sustainability. Waste is generated and consumed across all FEW elements. Wastewater streams are generated in the production and processing of most foods, in energy generation, and in the production of certain water sources (e.g., desalination processes). Indeed, the production, processing, and transport of liquid energy sources are notorious for the creation of wastewaters, as are fossil-fuel-burning energy plants (e.g., coal ash and scrubber waste streams) and nuclear facilities (e.g., hot water discharges). Food wastes vary significantly with the type of product and its distribution along the supply chain. For example, cereal grains are disproportionately lost in the field, while vegetables are mainly lost during retail or in private households [29].

Technology innovations create new processes and products, which may range from algal-based hydrogen and hydrocarbon production to carbon dioxide capture and fuel production via electrosynthesis, improved stress- (e.g., drought-) tolerant plants, and more efficient and alternative methods for meat production. The recycling, reuse, and reclamation of waste materials have demonstrated benefits throughout all FEW elements. As a result of current technology development (e.g., artificial intelligence), food-production capabilities in the built environment will substantially contribute to growth in urban agriculture [30]. These technologies may likewise facilitate agricultural production in harsh and contaminant-stressed areas. For example, nanotechnology integration can greatly increase the efficiencies of wastewater treatment, water desalination, and renewable energy generation via solar cells, enabling food production in unfavorable environments. Other technologies (e.g., gene-editing technology and digital technology) also have great potential for enhancing the FEW nexus by, for example, minimizing crop vulnerability to natural environmental impacts such as disease spread and extreme climatic events, reducing chemical fertilizer use, and increasing ecosystem service value [31].

Sustainable outputs of FEW systems include nutritious and plentiful food, necessary energy, and potable water, without compromising crucial ecosystem services such as clean air or infringing on the cultural heritage of societal groups [32]. Meanwhile, FEW resources must meet energy demands and water requirements without violating national sovereignty, which remains an unresolved political issue. There is a need to view FEW systems through a sustainability lens in order to ameliorate existing negative impacts on the environment and ecosystem health [33,34]. From a natural ecosystem perspective, it may be arguable that food production at the scale needed to support humankind can never be truly sustainable. FEW nexus solutions to this issue must thus ensure that ecosystem functions and services are maintained at local, regional, and global levels. Here, engineering interventions at multiple scales are a crucial solution, among others [18]. Such interventions will improve scientific understanding, deliver engineering solutions in the near term, and prompt the transition from natural ecosystems to managed ecosystems (e.g., urban agriculture) with low FEW footprints. Such developments may appear unacceptable to traditional environmentalists; thus, a debate to determine the meaning of "low FEW footprints" may be required. It will be interesting to see how policymakers balance stakeholder interests at the international level and ultimately deliver solutions that address the FEW nexus at a global scale.

Social sustainability determines the fate of FEW nexus solutions. This is because, in order to create any real change, scientists, policymakers, and the general public alike must understand and agree with the FEW initiative [13,35]. Public engagement events and outreach opportunities provide reliable channels through which to understand the needs of the people and grasp the issues of concern to them. The results of these public events will effectively complement and (one hopes) support the findings and recommendations of the expert international research community. Building the best model will not achieve anything if the population at large fails to understand. The international FEW agenda necessitates global acceptance—not only in geographic terms, but also in terms of the social context. Furthermore, in order to succeed, the agenda must engage all segments of society and leave no stakeholder groups behind [36].

3. Scalability of FEW research enterprise

The research enterprise framework shown in Fig. 1 illustrates the hierarchical structure of the system-in-system network that underlies FEW and ESS interactions. This framework provides general guidance for identifying knowledge gaps in a logical manner, defining inter-sectorial relations in terms of management efficiency, and prioritizing FEW nexus research from a transdisciplinary perspective. When the framework is applied, attention should be paid to disparity, interactions, and tradeoffs at different scales. For example, from the local to national to international scales, disparity exists in the quantity and quality of available FEW resources that are necessary to sustain populations. This disparity is related to the agricultural production of food, but even more to economic, behavioral, and political factors. The disparity is enlarged by competition for the energy and water resources needed in agriculture and by imbalanced food and energy trades among countries [27]. In the near term, waste minimization and resource recovery and reutilization—which are at the core of a circular economy—will play an increasingly important role in ameliorating the disparity in the availability of FEW resources. Of course, sociological and behavioral acceptance of what constitutes suitable FEW products is a prerequisite to closing the gap [27]. Simple consumer preferences, such as a preference for unblemished over blemished produce, the embrace or rejection of genetically modified foods, or a preference for traceable and authenticable foods over conventionally supplied foods, may be driven entirely by different marketing (e.g., niches in the global supply chain), production (e.g., with treated water), and/or political rationales.

The cost of sustainable development depends on local to international scales of accessibility to, and competition for, FEW resources (Fig. 2) [33]. At smaller scales, the FEW network provides limited accessibility to various resources. This limitation could be worsened by high exploitation of local water and land resources, inter-sectorial competition, waste accumulation, and short supply chains. Such an EES system, with low accessibility of FEW resources, generally has a low resilience to challenges (e.g., climate change and economic depression), which eventually increases the cost of sustainable development. The large water and energy costs needed to increase food self-sufficiency in Qatar, a country in a super-arid region, are one example. According to a recent assessment [5], a 25% increase in self-sufficiency demands an 82% increase in water use; an 82% increase in energy use for groundwater withdrawal; a 97% increase in energy use for food production; and a 153% increase in land resources. It is obvious that the reliance of food production on local water and energy resources is not sustainable. The adoption of new technologies

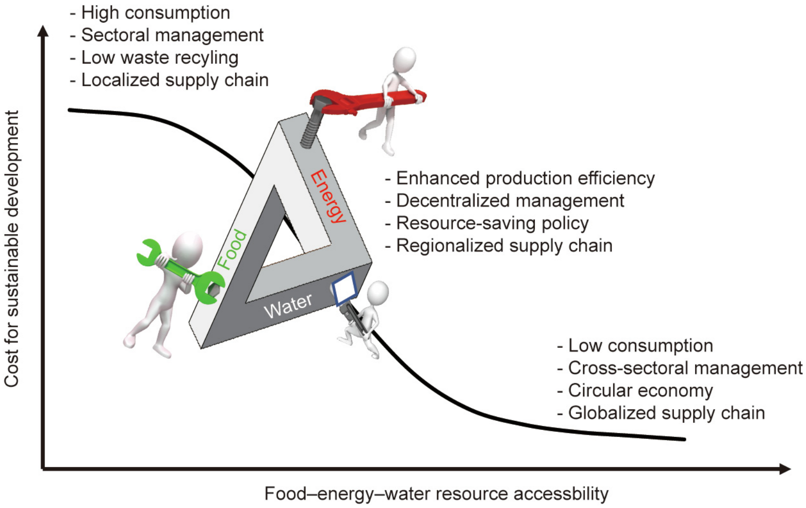


Fig. 2. The relationship between food–energy–water resource accessibility and the cost of sustainable development and associated influencing factors at different levels.

(e.g., drip irrigation technology and water-saving crop biotechnology) might help lower the cost, while another solution is to improve trade strategies for increasing and diversifying food imports. In contrast, at a larger scale, FEW resources and supplies are more easily coordinated via supply chains. A complementary supply can help not only in avoiding the overconsumption of local FEW resources and products, but also in increasing the resilience of FEW systems to stressors. As a result, the scaling-up of the FEW network reduces the cost of sustainable development. To further illustrate, excess water demands are already affecting major population centers across the globe. Some countries (e.g., Bangladesh) have therefore investigated the option of limiting water-intensive crop production in drier areas, which spares water resources for critical use elsewhere without affecting a country's ability to meet the goal of agricultural self-sufficiency [37]. Some countries (e.g., China) are expanding their FEW networks to the global scale by importing water-intensive foods (e.g., cereal grains), petroleum, and natural gas in order to save local water resources that are needed in other sectors [4]. Such choices illustrate a global society's ability to adapt to current population demographics and to strategically shift climate-change influences via regional or world trade partnerships. Globalization has already achieved positive economic improvements, both in developed countries, by enabling the smart sourcing of resources worldwide, and in developing countries, by reducing the exploitation of nonarable soils and increasing natural reforestation [38]. However, large uncertainties of global sustainability are rooted in each country's FEW resource accessibility [39]; net-saving trades of embodied FEW products between developing and developed countries are particularly critical to the realization of the United Nation's SDGs. Therefore, when applied, FEW research enterprise should fully consider these scale-dependent uncertainties, both strategically and tactically, such as importing food and energy with a low water footprint and transferring water with a low energy footprint for food production [4,40]. As conceptually illustrated in Fig. 2, efficient resource utilization through reducing consumption, balancing management across sectors, developing a circular economy, and expanding the supply-chain network is key to increasing the availability of FEW resources while decreasing the cost of sustainable development. It has been well documented that reducing the consumption of raw materials and energy can mitigate waste generation (e.g., plastics), while circular economies serve as a backup plan for recycling the wastes of FEW production [14]. Cross-sectorial management of FEW resources through policy-based coordination can greatly improve the efficiency of FEW production while enhancing natural resource conservation. For example, Ethiopia, Egypt, and Nepal have established new government agencies at the ministry level to coordinate water and energy uses in agriculture [8]. Supply-chain expansion by regionalizing and globalizing the trade of FEW products is a low-cost approach to developing resource-efficient societies [32,38,40].

4. Concluding remarks

FEW elements and interactions are ubiquitous in the entire EES system. This complexity challenges a clear definition of FEW-EES relationships and their nexus modeling. The proposed research enterprise framework attempts to define the interrelationships between EES and FEW system components. The framework emphasizes intra- and inter-system feedbacks that govern the nexus. The EES system, which encompasses economic processes (production–processing–transportation–storage–consumption), environmental change (influence–consequences–outcomes), and societal motivation (technology–output–sustainability), intertwines with the production and consumption of FEW resources. From a networking perspective (i.e., system-to-system connection), enterprise efforts prioritize the development of a shared, strategic vision for unpredictable changes to the FEW nexus from local to global scales in the context of socioeconomic adaptation to increasing food demand and climate change. As known and unknown environmental consequences emerge, enterprise efforts are believed to broaden and prioritize the tasks of FEW research and engagement activities (e.g., waste-based food production and agriculture in built environments), reduce the disparities of FEW security in different communities (e.g., globally versus locally sourced foods), and accelerate the acceptance of an FEW nexus policy by all stakeholders, including the general public.

Acknowledgments

This work was supported by the US National Science Foundation (CBET-1739474 and CBET-2021956). The authors are grateful for the constructive comments of anonymous reviewers.

Compliance with ethics guidelines

Jie Zhuang, Frank E. Löffler, and Gary S. Sayler declare that they have no conflict of interest or financial conflicts to disclose.

References

[1] Bleischwitz R, Spataru C, VanDeveer SD, Obersteiner M, van der Voet E, Johnson C, et al. Resource nexus perspectives towards the United Nations sustainable development goals. Nat Sustain 2018;1(12):737–43.

[2] Young OR, Guttman D, Qi Ye, Bachus K, Belis D, Cheng H, et al. Institutionalized governance processes: comparing environmental problem solving in China and the United States. Glob Environ Change 2015;31:163–73.

[3] Ghodsvali M, Krishnamurthy S, de Vries B. Review of transdisciplinary approaches to food–water–energy nexus: a guide towards sustainable development. Environ Sci Policy 2019;101:266–78.

[4] Zhuang J, Sun H, Sayler G, Kline KL, Dale VH, Jin M, et al. Food–energy–water crises in the United States and China: commonalities and asynchronous experiences support integration of global efforts. Environ Sci Technol 2021;55(3):1446–55.

[5] Daher BT, Mohtar RH. Water–energy–food (WEF) Nexus Tool 2.0: guiding integrative resource planning and decision-making. Water Intl 2015;40(5–6):748–71.

[6] Mohtar RH, Lawford R. Present and future of the water–energy–food nexus and the role of the community of practice. J Environ Stud Sci 2016;6(1):192–9.

[7] Simpson GB, Jewitt GPW. The development of the water–energy–food nexus as a framework for achieving resource security: a review. Front Environ Sci 2019;7:8.

[8] Rasul G, Neupane N. Improving policy coordination across the water, energy, and food, sectors in South Asia: a framework. Front Sustain Food Syst 2021;5:602475.

[9] Mohtar RH. An integrated sustainability index for effective water policy. In: Initiative TWEFW, editor. Water security: the water–food–energy–climate nexus. Washington; DC: Island Press; 2011. p. 217–9.

[10] Mahlknecht J, González-Bravo R, Loge FJ. Water–energy–food security: a nexus perspective of the current situation in Latin America and the Caribbean. Energy 2020;194:116824.

[11] Jha K, Doshi A, Patel P, Shah M. A comprehensive review on automation in agriculture using artificial intelligence. Artif Intell Agric 2019;2:1–12.

[12] Jung J, Maeda M, Chang A, Bhandari M, Ashapure A, Landivar-Bowles J. The potential of remote sensing and artificial intelligence as tools to improve the resilience of agriculture production systems. Curr Opin Biotechnol 2021;70:15–22.

[13] Rasul G, Sharma B. The nexus approach to water–energy–food security: an option for adaptation to climate change. Clim Policy 2016;16(6):682–702.

[14] Albrecht TR, Crootof A, Scott CA. The water–energy–food nexus: a systematic review of methods for nexus assessment. Environ Res Lett 2018;13(4):043002.

[15] Daher BT, Mohtar RH, Lee SH, Assi A. Modeling the water–energy–food nexus: a 7-question guideline. In: Salam PA, Shrestha S, Pandey VP, Anal Ak, editors. Water–energy–food nexus: principles and practices. Washington, DC: Wiley; 2017. p. 57–66.

[16] Anser MK, Yousaf Z, Usman B, Nassani AA, Qazi Abro MM, Zaman K. Management of water, energy, and food resources: go for green policies. J Cleaner Prod 2020;251:119662.

[17] United Nations Department of Economic and Social Affairs, Population Division. World population prospects: data pooklet. ST/ESA/SER. A/424. 2019.

[18] Scanlon BR, Ruddell BL, Reed PM, Hook RI, Zheng C, Tidwell VC, et al. The food–energy–water nexus: transforming science for society. Water Resour Res 2017;53(5):3550–6.

[19] Zhang S, Zheng M, Zhai H, Ma P, Lyu Y, Hu Y, et al. Effects of hexanal fumigation on fungal spoilage and grain quality of stored wheat. Grain Oil Sci Technol 2021;4(1):10–7.

[20] Schnell SM. Food miles, local eating, and community supported agriculture: putting local food in its place. Agric Hum Values 2013;30(4):615–28.

[21] US Department of Energy, Energy Information Administration, Independent Statistics and Analysis. Use of energy explained: energy use for transportation [Internet]. [updated 2021 May 17]. Available from: https://www.eia.gov/energyexplained/use-of-energy/transportation.php.

[22] Shepon A, Eshel G, Noor E, Milo R. The opportunity cost of animal-based diets exceeds all food losses. Proc Natl Acad Sci USA 2018;115(15):3804–9.

[23] Yang L, Wang Y, Wang R, Klemes JJ, de Almeida CMVB, Jin M, et al. Environmental–social–economic footprints of consumption and trade in the Asia-Pacific region. Nat Commun 2020;11:4490.

[24] Schröder P, Beckers B, Daniels S, Gnädinger F, Maestri E, Marmiroli N, et al. Intensify production, transform biomass to energy and novel goods and protect soils in Europe—a vision how to mobilize marginal lands. Sci Total Environ 2018;616–617:1101–23.

[25] Wong BBM, Candolin U. Behavioral responses to changing environments. Behav Ecol 2015;26(3):665–73.

[26] Yan Y, Wang YC, Feng CC, Wan PH, Chang KT. Potential distributional changes of invasive crop pest species associated with global climate change. Appl Geogr 2017;82:83–92.

[27] Olawuyi D. Sustainable development and the water–energy–food nexus: legal challenges and emerging solutions. Environ Sci Policy 2020;103:1–9.

[28] Kibler KM, Reinhart D, Hawkins C, Motlagh AM, Wright J. Food waste and the food–energy–water nexus: a review of food waste management alternatives. Waste Manage 2018;74:52–62.

[29] De Laurentiis V, Corrado S, Sala S. Quantifying household waste of fresh fruit and vegetables in the EU. Waste Manage 2018;77:238–51.

[30] Zhong T, Si Z, Shi L, Ma L, Liu S. Impact of state-led food localization on suburban districts' farmland use transformation: greenhouse farming expansion in Nanjing city region. China. Landsc Urban Plan 2020;202:103872.

[31] Heeb L, Jenner E, Cock MJW. Climate-smart pest management: building resilience of farms and landscapes to changing pest threats. J Pest Sci 2019;92(3):951–69.

[32] Deng HM, Wang C, Cai WJ, Liu Y, Zhang LX. Managing the water–energy–food nexus in China by adjusting critical final demands and supply chains: an input–output analysis. Sci Total Environ 2020;720:137635.

[33] D'Odorico P, Davis KF, Rosa L, Carr JA, Chiarelli D, Dell'Angelo J, et al. The global food–energy–water nexus. Rev Geophys 2018;56(3):456–531.

[34] Slorach PC, Jeswani HK, Cuéllar-Franca R, Azapagic A. Environmental sustainability in the food–energy–water–health nexus: a new methodology and an application to food waste in a circular economy. Waste Manage 2020;113:359–68.

[35] van Gevelt T. The water–energy–food nexus: bridging the science–policy divide. Curr Opin Environ Sci Health 2020;13:6–10.

[36] Liebenguth J. Conceptions of security in global environmental disclosures: exploring the water–energy–food security nexus. Crit Stud Secur 2020;8(3):189–202.

[37] Akanda MAI. Seasonal and regional limits to growth of water-intensive crop farming in Bangladesh. Sustain Water Resour Manag 2019;5(2):817–30.

[38] Nathaniel SP, Nwulu N, Bekun F. Natural resource, globalization, urbanization, human capital, and environmental degradation in Latin American and Caribbean countries. Environ Sci Pollut Res 2021;28(5):6207–21.

[39] Yu L, Xiao Y, Zeng XT, Li YP, Fan YR. Planning water–energy–food nexus system management under multi-level and uncertainty. J Clean Prod 2020;251:119658.

[40] Shtull-Trauring E, Bernstein N. Virtual water flows and water-footprint of agricultural crop production, import and export: A case study for Israel. Sci Total Environ 2018;622-623:1438–47.