Environmental sustainability: a review of the water–energy–food nexus

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ABSTRACT

Water, energy, and food are primary resources on which human life is dependent. This paper presents a review of the water–energy–food (WEF) nexus considering the environmental impacts generated by humans' reliance on water, energy, and food for their subsistence. Our review assesses the WEF with respect to the agricultural, industrial, and urban sectors and their use of water, energy, and food. The multi-sectorial assessment addresses options for improved management that avoids or mitigates adverse impacts in the agricultural, industrial, and urban sectors. Activities such as the use of fertilizers and pesticides in the agricultural sector, for instance, cause water, air, and soil pollution, which leads to social calamities and environmental degradation. Therefore, examining the effects of mismanagement in one sector on other sectors from the perspective of the WEF nexus is necessary for improved resource management and environmental protection. A literature review revealed that factors or practices of resources use influence sectors differently and with varying degrees of effectiveness in reducing the environmental damage caused by resources use. Improved social awareness on resource consumption, the use of renewable energy, improved energy efficiency, the reduction of food waste, improved animal husbandry, and other factors involved in the WEF nexus are herein examined. This paper's analysis demonstrates that every action and manner of resource use in one sector also affects other sectors and their resources use, thus calling for a unified analysis of the WE nexus.

Key words | environment, interdisciplinary, security, water–energy–food nexus

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HIGHLIGHTS

- Demonstrating that every action and manner of resource use in one sector affects other sectors and their resources use, as well, thus calling for a unified analysis of the WE nexus.
- Covering a variety of topics pertinent to the WEF nexus and the environment.
- Assessing the environmental impacts of resource consumption in the agricultural, industrial, and urban sectors.

INTRODUCTION

Water, energy, and food are essential resources for the successful functioning of society. Freshwater used by humans derives from precipitation, rivers, streams, lakes, reservoirs, and aquifers. Reservoirs are hydraulic structures built to store, deliver, and regulate water for multiple uses and functions (Asgari *et al.* 2016). In addition to water supply, many reservoirs provide flood control protection, generate hydropower, provide recreational services, and

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maintain environmental flow requirements through streamflow regulation. Most water use and water-related services rely on energy for its storage, withdrawal, conveyance, and treatment. There is a worldwide increase in the production of renewable energy (wind and solar, primarily), although non-renewable energy (fossil fuels such as coal, petroleum, oil, and natural gas) remains predominant (Loáiciga 2011). Energy consumption from fossil fuels produces air pollution by the emission of greenhouse gases (GHGs). Other sources of energy are hydropower, nuclear power, geothermal power, and biomass (biofuels, bio-power, traditional fuels, etc.).

Demand for food is increasing with the growing population worldwide, and it is estimated to increase by 35% by 2030 (USNIC 2012). Food production stems from agriculture and ecosystems. Agricultural products include crops and livestock, and ecosystem products derive from forests and fisheries. It is estimated that agricultural production must increase by about 70% by 2050 to feed the world's population. Such a rise in production must rely on improved mechanization, enhanced fertilization, and efficient irrigation, which commonly means rising consumption of water and energy (UNESCO-IHE 2013). Food availability is affected by production, distribution, trade, and access to food depending on affordability, distribution, availability, safety, and dietary choices (Leck et al. 2015).

The water–energy–food nexus

The nexus principle is to create more with fewer resources. A water–energy–food (WEF) nexus approach must address the integrated planning of infrastructure for water, wastewater, and energy, and it commonly differs across low-, mid-, and high-income regions. The WEF nexus is an interdisciplinary method of study that encompasses social, economic, political, and environmental factors (Figure 1).

Interdisciplinarity is a key challenge to achieve successful partnerships between the private and non-private sectors to develop systems modeling that evaluates trade-offs in WEF decision making (Scanlon et al. 2017). Wiegleb & Bruns (2018) argued that interdisciplinary inquiry is needed to develop a comprehensive understanding of the resource nexus. Kumazawa et al. (2017) cited an example of interdisciplinary concepts for the assessment of groundwater use involving groundwater pumping for geothermal power generation. Interdisciplinary assessment relies on a common language and a common theoretical basis (Defilia et al. 2006; Kumazawa et al. 2017). Therefore, nexus concepts are based on a conceptual framework shared by multiple involved analysts and stakeholders.

Siddiqi & Anadon (2011) demonstrated that the energy sector is weakly dependent on water resources; on the contrary, water withdrawal, desalination, and sewage treatment have a strong dependency on energy. Water is used in the extraction, cooling, and processing of fossil fuels. Energy is required for water distribution, storage, conveyance, desalination, and sewage treatment (Lam et al. 2017). Fossil fuel production is water-intensive; conversely, seawater desalination is an energy-intensive process. Desalinating water for drinking purposes requires 23 times more energy than that

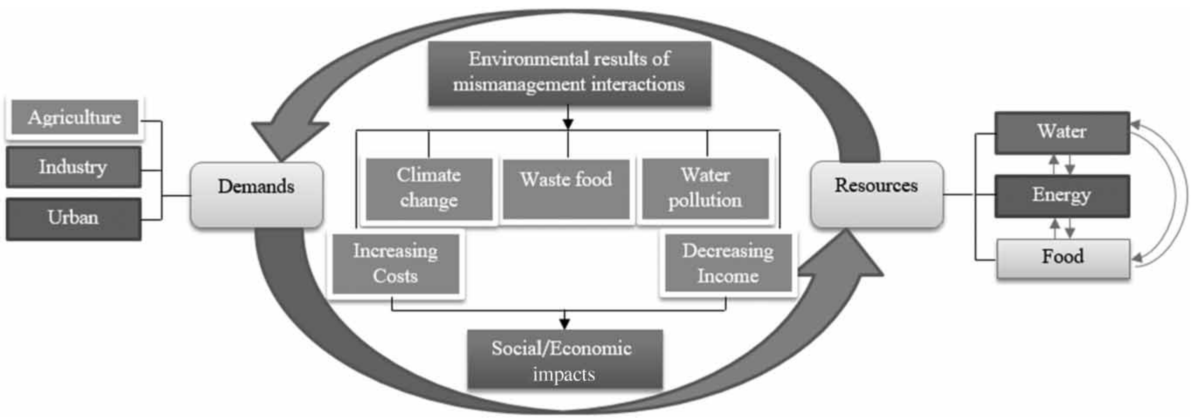

Figure 1 | Main components of the water–energy–food nexus and associated environmental impacts.

required to extract and treat surface water (Borgomeo *et al.* 2018).

Water and energy are necessary for food production. According to report 48 of the UNESCO-IHE (2013), the production of 1 kg of beef consumes approximately 15,000 l of water (93% green, 4% blue, and 3% gray water footprints). There is a large variation about this global average from region to region. The precise water footprint of beef depends on factors such as the type of production system and the composition and origin of the feed for bovines. The report 49 of the UNESCO-IHE (2013) states the water footprint of a 150-g soy burger produced in the Netherlands is about 160 l. A beef burger in the Netherlands costs consumes about 1,000 l of water. Food is required to generate bodily energy through physiologic processes.

The feedbacks between water, energy, and food are complex and dynamic, with actions in one of the agricultural, industrial, and urban sectors frequently affecting the other two sectors. The conceptualization of resources use as a nexus represents an effort to resolve the complexity of the interactions between water, food, energy, climate, and human activities (Howarth & Monasterolo 2016). Understanding the interactions and feedbacks between these water, energy, and food use must rely on methods that resort to interdisciplinary, multi-sectoral, and multi-dimensional research (Endo *et al.* 2017).

Ackoff (1999) defined a system a set of two or more elements that consists of the three following conditions. First, each element (or subsystem) of a system affects the behavior or features of the whole system. Second, there is an interdependence between the elements of the system that affects the entire system. Third, any subset of the elements affects the entire system, and this effect depends on at least one other subset of the system. In other words, the components of a system are interconnected such that no independent subgroup can be formed. A system so defined implies that the interactions between water, food, and energy can be considered as a system because changes in the amount of consumption and sources of each of these three resources affect the others. For instance, the amount of agricultural production, and the choice of crop type and irrigation method depends on the availability of water resources. Clearly, water, energy, and food form a system that, in turn, is a subsystem of the social and economic system.

Interactions in the WEF nexus are summarized below:

- The effect of energy on food production (Pimentel & Pimentel 1985; Wang 2013; Garcia & You 2016; Ladha-Sabur *et al.* 2019):
  - Energy is used in food preparation, food processing, cooking, thermal sterilization, freezing of food, transportation, etc.
- The effect of energy on water (Siddiqi & Anadon 2011; Karimi *et al.* 2012; Kumazawa *et al.* 2017; Lam *et al.* 2017; Terrapon-Pfaff *et al.* 2018):
  - Energy is used to heat water in homes, pumping, water collection, water purification, water storage, water distribution, etc. (Soltanjalili *et al.* 2011).
- The effect of water in food production (D'Odorico *et al.* 2018):
  - Water is used in food production, washing, transportation, food preparation and cooking, food processing, etc.
- The effect of water on energy (Jalilov *et al.* 2016):
  - Water is used to generate electricity (power plants), cooling in various industrial plants, etc.

Providing water to meet growing human demand implies heavier reliance on resources (water, energy, and land) to meet human needs and demand food, which concomitant larger stress on the environment by increasing water diversions, pollution, and changes to the natural environment created by human activities. These environmental impacts must be considered in WEF nexus studies to achieve holistic and effective strategies for resource management.

Understanding the interdependence of water, energy, and food, and the environmental impacts of human reliance on these commodities is a pressing and timely matter. The provision of secure food supplies, water, and clean, renewable, and reliable energy is essential to realize sustainable development. The WEF nexus must be understood and managed properly to maximize the underlying synergies and reduce or avoid adverse impacts from human reliance on water, energy, and food consumption.

Objective

Most previous studies related to the environment and water, energy, or food address only partially, or in a non-integrated manner, the use of water, energy, and food. Yet, there is interdependency in the use of water, energy, and food, which calls for their integrated analysis for the purpose of sustainable resource management. A meaningful understanding of the WEF nexus is only achievable by the comprehensive study of water, energy, and food. This paper's objective is the study of the WEF nexus for assessing the environmental impacts of resource consumption in the agricultural, industrial, and urban sectors. This paper covers a variety of topics pertinent to the WEF nexus and the environment. Figure 1 depicts a conceptualization of the framework of the WEF nexus system proposed in this work. Figure 1 shows three main resources (water, energy, and food) whose use is interrelated in the agricultural, industrial, and urban sectors. The interactions between resources availability and use may cause adverse environmental impacts, social calamities, and economic inefficiency.

The environmental impacts that occur in the WEF nexus and interactions between water, energy, and food are discussed in the following section.

ENVIRONMENTAL IMPACTS IN THE WEF NEXUS

The environment includes conditions in which all living things can live and operate, and makes up our surroundings. This research considers air, water, and soil as the environment that are constantly affected and harmed by various human activities including emission of GHGs (climate change), soil pollution and erosion, depletion and degradation of water resources, deforestation, reduction of biodiversity, and fisheries depletion.

The use of water, energy, and food for providing human demands have positive and negative impacts on the environment, among which are water resources quality and quantity, air and soil quality, and public health. Positive effects arise from the use of one type of resource in the production of other resources. Negative effects may cause pollution and endangerment of human health. Flowing water can transport pollutants causing adverse effects on humans and wild life (Farhadian *et al.* 2016). Contrary to traditional energy analysis methods, ecosystem issues related to socio-economic studies are included in the energy and water resources accounting to reflect issues such as carbon sequestration and pollution reduction (Wang *et al.* 2017). Environmental degradation such as water and air pollution compromise the sustainability of resources. The emission of GHGs by reliance on fossil fuels in the post-Industrial Revolution era poses threats to society and the environment that may reduce water storage on land thus affecting energy and food resources. For instance, hydropower generation may be reduced by modern climate change (Jahandideh-Tehrani *et al.* 2015), which would render agricultural production less reliable, therefore endangering food security. Food production requires water, energy, and food resources. Energy production involves water, and, in turn, water production requires energy for extraction and transfer.

The literature on the impacts of the WEF nexus mostly has focused on climate change and GHGs as environmental impacts. For instance, Conway *et al.* (2015) assessed the link between climate and the relation between water, food, and energy in South Africa. They stated that climate change causes fluctuations in WEF components such as agricultural production, water availability, as well as energy production and demand. Also, rising demand is increasing pressure on WEF nexus. Rasul & Sharma (2016) investigated the impact of climate change on future planning and assessed policy decisions in the Hindu Kush Himalayan region seeking to decipher the complexity of feedbacks between water, food, and energy. The latter authors contended that studies of this type concerning South Asia, where climate change has exacerbated the challenges of meeting resources demand, have not been taken into account between the nexus sectors, and, so far, scant effort has been made to understand the nexus interactions and climate change. Yang *et al.* (2016) concluded that the water, food, energy, and climate change feedbacks are central to decision making about water policies and management, especially, concerning international transboundary basins.

Howarth & Monasterolo (2017) reported an approach that yields clear and accessible results for better understanding of the interconnectedness between water, food, energy, and climate change, and concluded the water, food, energy, and climate change feedbacks are non-linear, multi-sectoral, and time-sensitive. Wang et al. (2019) showed that exchanges between energy, water, and carbon emissions provide insights for nexus management on how to balance water scarcity issues and develop future energy production in energy and water resources planning. They investigated five scenarios (four low-carbon-development scenarios (S2–S5) and one baseline scenario (S1)) by input–output analysis to reduce climate change impacts.

Figure 2 displays the interactions between water, energy, and food resources in the form of a Venn diagram. It is seen in Figure 2 that climate change can affect the availability of water through precipitation and by modifying evaporation. Climate change may affect the use of energy through heating and cooling requirements of human activities.

Regarding climate change, warmer surface air temperature would raise reliance on air conditioning and raise the energy demand. For example, Middle Eastern and Northern African (MENA) countries have the greatest potential for wind and solar energy production. The exploitation of their renewable energy capacities would assist MENA countries in improving energy supply. Also, greater reliance on wind and solar energies would increase electricity production to meet their development needs (Scherr 2018).

The water–energy–food–environment nexus is a concept that stresses the importance of the interactions between the WEF nexus and the environment. This study considers surface water and groundwater, soil, and climate, which affect water, energy, and food sources through a set of complex

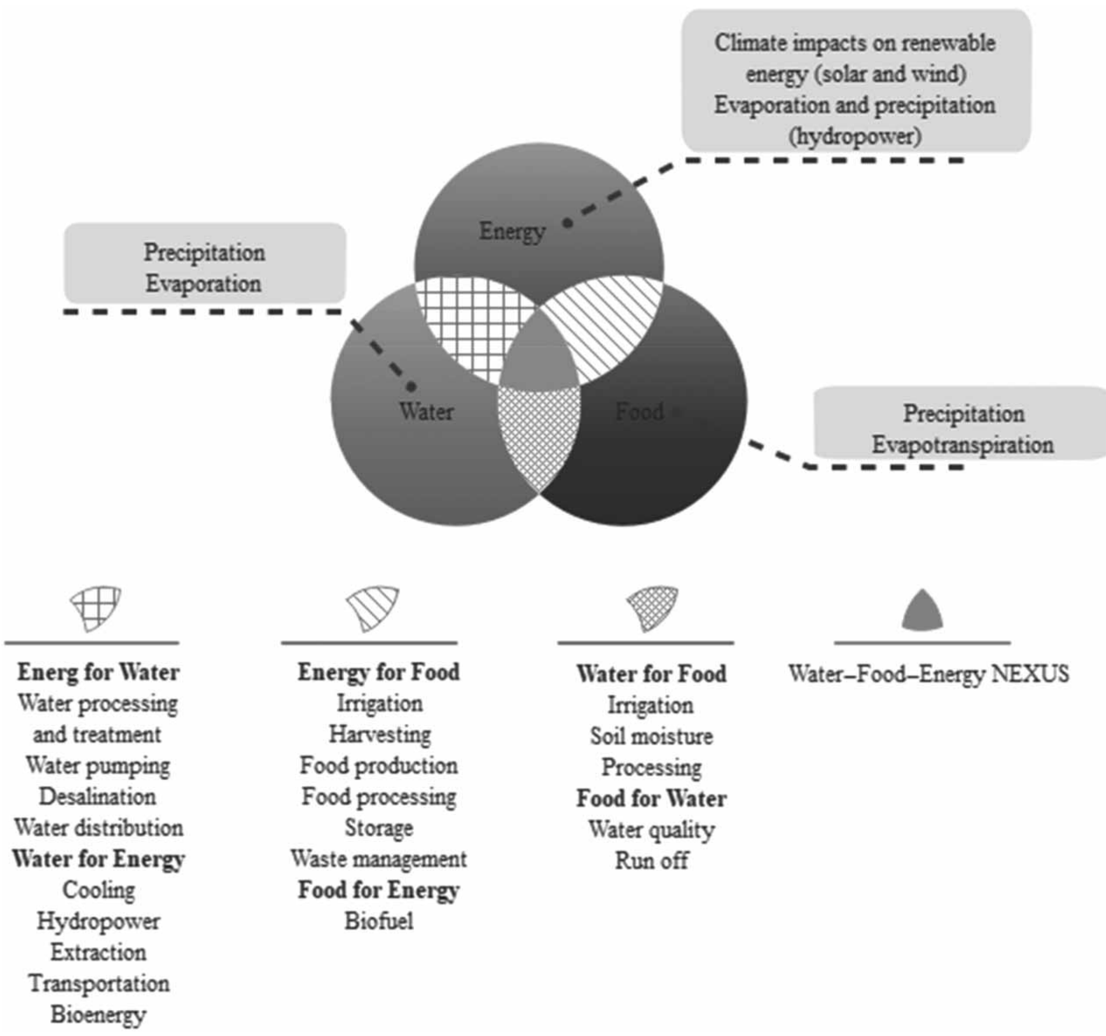

Figure 2 | Venn diagram of interactions in the water–energy–food nexus.

feedbacks and interactions. The review of such interactions in this study demonstrates that actions taken in the agricultural, industrial, and urban sectors influence the WEF nexus, and the consequences of such actions must be carefully assessed to avoid adverse and irreversible impacts that may negate short-term gains. Improving water-use and energy efficiency is imperative to avoiding deleterious environmental impacts (Khan *et al.* 2009).

The next sub-sections review environmental impacts that arise in the agricultural, industrial, and urban sectors.

The agricultural sector

Food production involves water and energy inputs according to crop type, growing season, and food type (Shannak & Vittorio 2018). Enhancing food production means enlarging the cultivated area and the application of pesticides and fertilizers, which may create adverse environmental effects (Ericksen 2008), such as increasing water demands for irrigation (Molden & Fraiture 2004), increasing pollution by agricultural inputs that degrade soils (Pretty *et al.* 2005), and increasing energy demands for food production (Matson *et al.* 1997). Yang & Wi (2018) established that days with no pollutants discharge from farmland can be significantly increased by improved irrigation efficiency and agricultural management. Markantonis *et al.* (2019) showed that agricultural practices, urban growth, water scarcity, and other issues underlies the provision of suitable water in the Middle East and to ecosystem decline. They contended that improper agricultural practices have led to underperformance of the agricultural sector and the depletion of water and soil resources. Water pollution, food waste, and waste generation, in general, are other calamities in the Middle East.

Increase of water withdrawals means higher energy demand. In fact, besides pumping groundwater for irrigation, all other agricultural activities such as land preparation, crop harvesting, fertilizer application, pest control, and food transport require energy inputs with associated environmental effects (Searchinger et al. 2008). Terrapon-Pfaff *et al.* (2018) argued that provision of energy (say, for pumping water) has had negative effects on the environment, and that the use of renewable sources of energy would not pose negative effects on resources.

Fertilizer requires energy in its production and is applied to increase crop yields. The use of non-renewable energy to produce fertilizer triggers water and food chain pollution, and exacerbates GHG emissions. The long-term application of fertilizers may cause negative impacts on human health and ecosystems, also (Khan *et al.* 2009). They believe that irrigation is a leading energy user in agriculture, which means that achievement of high water efficiency while increasing agricultural productivity is essential to achieve food security and environmental protection.

Khan *et al.* (2009) explored ways to decrease energy input in agricultural operations and argued that sowing and harvesting are major energy users after irrigation and the application of agrochemicals. This research recommended technological innovation in the sowing and harvesting practices to reduce the use of fossil fuel in agricultural machinery and negative environmental impacts. Horowitz & Gottieb (2010) argued that one of the causes of GHG emissions in the agricultural sector is livestock and dairy operations, which are emitted through the ruminant process. They stated that methane emissions could be reduced by changing animal feed. They also said that installing solar panels or wind turbines on farms could reduce GHG emissions. Rasul (2014) reported that biomass use for cooking and heating affects the water, energy, and food nexus, and heightens the emission of black carbon (aerosol particles in the atmosphere that contributes to atmospheric warming; Venkataraman *et al.* 2005), and to preserve the Himalayan glacier ecosystem to supply freshwater downstream and control carbon dioxide emissions suggested providing clean energy options for rural people (such as solar, biomass, and biogas furnaces) and improving furnace efficiency in the brick industry. Large quantities of food are wasted in today's world, which are discharged to the environment thus causing degradation. Treatment and disposal of wasted food must be supervised and regulated. Energy production from such waste must be considered to obtain clean and renewable energies such as bioethanol, biodiesel, bio-oil, biogas, synthetic gas, therefore reducing waste disposal and raising clean energy generation.

The industrial sector

The importance of using water, food, and energy inputs in industrial production has been addressed in previous works. Less attention has been paid to the relevance that the input of such resources in industrial processes has on the environment. In some countries, Kazakhstan being a case in point, coal power stations account for the majority of the water withdrawals in the energy sector (Karatayev *et al.* 2017). The latter authors stated that with the current energy mix, the amount of water use is expected to grow rapidly in the energy sector.

The industry sector is a major consumer of water and energy and is also a source of pollution. This means that addressing the industry sector from a water, food, energy, and environmental perspective is particularly important. Manufacturing plants input water for process mixing, chemical reactions, extraction, process cooling, steam generation, product washing, and equipment sanitization. Energy is required to power electric motors, operate pumps, run machinery, light floor-space, heat processes, and generate steam (Walker *et al.* 2013). All of these activities exacerbate demands on energy and water sectors. The use of innovative energy recovery technologies in wastewater treatment plants can reduce energy consumption (Stillwell *et al.* 2010).

The industrial sector, in addition to requiring water inputs and discharging polluted water (quantitatively and qualitatively), can pollute the air (Scott *et al.* 2016), thereby contributing to climate change and have probable adverse effects on water resources. The production of energy from fossil fuels to power the industrial sector affects the climate (i.e., through greenhouse gases, GHGs, such as carbon dioxide (CO_2), nitrogen oxide (N_2O), and methane (CH_4); Kumar & Saroj 2014) and pollutes the air with toxicants harmful to organisms (e.g., particulate matter; sulfur dioxide, SO_2; and nitrogen dioxide, NO_2; carbon monoxide, CO). GHG emissions contribute to climate change, alter the environment, and may reduce the available water resources in many parts of the world.

All industrial activities follow a lineal sequence, starting with the extraction of raw materials, and the use of technology and labor to convert them into value-added products. Fossil fuels are often used to generate energy during these stages, which results in the release of large amounts of CO_2. Also, the transport of raw materials to make them available for processing in industrial processes, and transporting the finished products for delivery to consumers causes emissions of pollutants such as carbon monoxide, nitrogen oxides, hydrocarbons, ozone, and particulate matter. The production of pollution-generating energy can be avoided by resorting to clean (i.e., pollution free) and renewable energy.

Hydropower produces about 16% of the electrical energy worldwide. It is considered renewable in the case of run-of-river hydropower generation, and only partly so when it requires reservoirs for a generation due to sedimentation that limits the useful life of reservoirs, not to mention the flooding of land, the alteration of streamflow patterns and their multiple destabilizing effects (Bazilian *et al.* 2011; Biemans *et al.* 2015). The creation of reservoirs for hydropower generation must address the downstream environmental flow requirements and the impacts of altered sediment transport and flow regime on geomorphic processes.

Continuing the lineal sequence produced by industrial activities is the generation of waste from manufacturing processes, which are disposed of in the environment sometimes along with the products themselves (Hawken *et al.* 2013), worsening environmental pollution. These wastes may be converted to energy through various methods such as fermentation, anaerobic digestion, and biological conversion in some cases, which lessens the burden of waste disposal on the environment and expands the energy sources. One of the important sources of biologic waste stems from food processing plants (factories). One way to convert this bio-waste into energy is through anaerobic digestion, a biochemical technology used to treat organic wastes and produce biogas, which can be served as fuel for heating or producing electricity and heat (El-Mashad & Zhang 2010). Afilal *et al.* (2010) evaluated the biogas potential of organic waste in the northernmost province of Morocco. They estimated the amounts of wastes in the study area and converted them to biogas to calculate the annual biogas energy potential of various wastes such as crop residues, livestock manure, municipal waste, and industrial waste (4,178,060 MWh), which accounted for 7,560 MWh from the food industry waste annually.

Economic progress is directly related to energy consumption, and as the population grows the demand for energy rises. Part of the energy required by various industries, including the food industry, can be met from the waste generated during the production phase. Navarro *et al.* (2012) investigated the use of lime industry wastewater for biogas production by anaerobic digestion, and reported that this process on an industrial scale could solve the problem of wastewater contamination and generate energy that could be consumed by the same industry.

Al-Ansari et al. (2016) proposed reducing these adverse environmental impacts (waste discharge to the environment and CO_2 emissions) on the WEF nexus with novel waste management techniques, which may take the form of biomass integrated gasification combined cycle (BIGCC) that recycles solid waste into useful forms of energy for reuse, or a carbon capture (CC) subsystem for the capture and recycling of CO_2 from combined cycle gas turbine plant (CCGT) and BIGCC.

Burning fossil fuels produces GHGs and carbon emissions. In the view of current climate change impacts, the world must transition to reliance on clean and renewable energy sources that eliminate harmful emissions and pollution. Electricity and heat emissions accounted for about 25% of the global emissions of GHGs in 2010, while industrial emissions accounted for about 21% of the GHG emissions the same year (IPCC 2014).

The urban sector

Cities emit large amounts of GHGs due to the multiple activities requiring energy that go on indefinitely within their boundaries (Pichler et al. 2017). Water pumping, treating, and distribution are energy-intensive and ubiquitous in urban areas, but water policies have large effects on the well-being of rural populations, also (de Silva et al. 2014). Electricity powers most of these water supply systems (Cook et al. 2012; Olsson 2012; Lam et al. 2017). Energy used for cooking, heating, and lighting in rural areas issues from a variety of sources. In some countries that energy source is primarily solid fuels like wood, coal, and kerosene rather than modern energy sources.

Lam et al. (2017) showed that there are factors that cause variations in the amount of energy used by cities. These factors are climate, topography, operational efficiency, and water use patterns. Urbanization frequently causes environmental degradation. Kumar & Saroj (2014) evaluated energy production and consumption, water use, and pollution and applied integrated approaches in the analysis of the water, energy, and pollution nexus in Delhi, India, and employed a three-step nexus approach, i.e., water–energy nexus, energy–pollution nexus, and water–energy–pollution nexus. The energy–pollution nexus focused on power plants and the transportation sector to conclude that energy production and consumption in power plants accounted for most of GHG emissions. The transportation sector accounted for most of the health-threatening emissions. The latter authors recommended using 'greener' fuel for power plants and transportation could reduce GHGs and health-threatening emissions, and demonstrated that the water–energy–pollution nexus is useful in decreasing negative impacts on water and air quality in the urban sector.

Nair et al. (2014) reviewed GHG emissions employing the water–energy–GHG nexus in urban water systems in the USA, UK, and Australia. They estimated the energy consumption of water (i.e., production and supply of water, extraction, treatment, desalination, etc.) that produced GHG emissions and classified the energy use in urban systems as operational (direct) energy use or embedded (indirect) energy use. Their results established that there is a research gap in the evaluation of energy use and its environmental effects, and they reported that suitable nexus methodology is not applied in various systems and regions.

Table 1 summarizes the causes of climate change by the emissions of GHGs in the agricultural, industrial, and urban sectors. Table 2 summarizes water, energy, and food consumption in the agricultural, industrial, and urban sectors and their environmental impacts. Adverse environmental issues created by the use of water, energy, and food are found the world over, as documented in Asia (Rasul 2014; Jalilov et al. 2016), Australia (Kenway et al. 2008; Khan et al. 2009), Africa (Enfors 2013; Pradeleix et al. 2014; Conway et al. 2015), North American, and Latin American countries (Gourdji et al. 2014).

THE ROLE OF GROUNDWATER ON THE WEF NEXUS

Groundwater is an important component of the WEF nexus in the agricultural, industrial, and urban sectors.

The agricultural sector

Sahoo et al. (2017) argued that climate, groundwater extraction, and surface water flows have complex non-linear

Table 1 | Causes of climate change and recommended solutions

Sectors	Greenhouse gas emission	Solutions
Agriculture	Use of non-renewable energy (fossil fuel) to produce fertilizer The transportation sector Livestock and dairy operations Groundwater pumping	• Using 'greener' fuel for power plants and transportation (Kumar & Saroj 2014) • Changing livestock feeds, installing solar panels or wind turbines on farms (Horowitz & Gottieb 2010) • Reducing food waste and use climate-friendly food (Government of the Netherlands) • Increasing the consumption of renewable fuels (Government of the Netherlands)
Industry	Production of energy to power the industrial sector Energy production and consumption in power plants and industry Industrial process The transportation sector	
Urban	The transportation sector Energy consumption for production and water extraction, treatment, and desalination	

relationships with groundwater levels in agricultural areas. They developed a modeling approach based on spectral analysis, machine learning, and uncertainty analysis as an alternative to complex physical and expensive computational models. They also applied and evaluated their modeling approach to two aquifer systems supporting agricultural production in the United States: the High Plains Aquifer and the Mississippi River Valley alluvial aquifer. Their results established that the demand for irrigation has the greatest effect on the groundwater level in most wells.

It is possible to reduce surface and groundwater inputs in the agricultural sector by increasing crop yields through the use of fertilizers. Yet, there may be adverse consequences by the use of fertilizers. Sekhon (1995) demonstrated that nitrogen fertilizer application may pose a threat of groundwater contamination when not applied judiciously. Fertilizer application efficiency is generally high in irrigated agriculture; yet, poor performance in fertilization, irrigation, or soil management can lead to reduced fertilizer application efficiency and significant nitrogen fertilizer leakage to groundwater.

Mirzaei *et al.* (2019) conducted a study on the use of groundwater, food, and energy nexus in Iran's agricultural sector. An analysis of this nexus reveals some of the main reasons for the worsening of Iran's water-shortage problems. Access to water (surface and groundwater) and energy subsidies have been one of the pillars of agricultural development policies in Iran, where the use of water to produce crops has exceeded the country's renewable water supply capacity. A significant reduction in groundwater levels across the country and increased energy consumption underscore the inefficient feedback between agricultural water, energy price, and groundwater withdrawal in an inefficient agricultural sector. Therefore, the implementation of holistic policy reforms is necessary to reduce agricultural water use. Such reforms would facilitate the modernization of the agricultural sector through technology transfer and implementation programs, supported by the implementation of complementary policies and regulations to improve groundwater monitoring and management (Fallah-Mehdipour *et al.* 2014).

Karimi *et al.* (2012) estimated that groundwater pumping in Iran consumes 20.5 billion kilowatt hours of electricity and 2 billion liters of diesel and accounts for 3.6% of Iran's total carbon emissions. This work assessed the possibility of water conservation in the agricultural sector by applying the soil, water, atmosphere, and plant (SWAP) model to simulate crop growth and field water balance for three crops (wheat, corn, and sugar beet) in the Gamasiab River Basin, Iran. The results indicate that the adoption of improved irrigation scheduling and water-application efficiency would lead to a 40% reduction in energy consumption and the associated reduction of carbon emissions triggered by groundwater use.

The industrial sector

Injection of water to extract oil and gas may threaten aquifers. Excessive groundwater discharge into streams can

Table 2 | Environmental issues associated with the water-energy-food nexus

	Agricultural activities	**Environmental impacts**	**Industrial activities**	**Environmental impacts**	**Urban activities**	**Environmental impacts**
Using water	Pumping (irrigation)	Declining groundwater level, degradation of rivers and ecosystems; deterioration of water quality	Heating and cooling systems	Generating pollutants, raising water temperature and changing species habitat, declining biodiversity	Heating and cooling	GHG emission
	Livestock (digestion of ruminants)	Water pollution, GHG emission				
	Producing biomass (fuel)	Deforestation, disruption of local water resources	Thermal cooling of power plants (to generate steam)	Killing fish, raising water temperature	Cooking	Water pollution
	Producing food	Deterioration of water quality, declining biodiversity	Electricity generation (fuel)	Degrade habitat and aquatic species	Drinking and hygiene	Water pollution
Using energy	Pumping (irrigation)	GHG emissions	Heating and cooling systems	CO_2 emission, release of pollutants to the environment	Cooking	GHG emissions
	Producing biomass (fuel)	Carbon emission			Heating and cooling	
	Producing food	Air pollution	Food processing	Pollution of surface and groundwater	Washing	
	Fertilizer	Water and soil pollution, threats to human health			Electrical appliances	
	Sowing	Introduce invasive species and alter biomass	Electricity generation (fuel)	CO_2 emission	Water treatment	
	Transportation	Carbon emission			Sanitation	
	Harvesting	Water pollution, Threats to human health			Lighting	
Using food	Livestock	GHG emissions, impacts on land use and biodiversity by grazing	–	–	Food consumption	Wasted food
	Producing biofuels	–				

lead to erosion and alter aquatic ecosystems (United States Department of the Interior 2002).

Accidental oil spills by industries have occurred multiple times. In fact, hydrocarbons and their microbial metabolites poison the soil ecosystem and pollute groundwater. The mechanical removal of contaminated soil layer is feasible in cases where the volume of oil-contaminated soil is limited in surface and depth, although this remedial method may be expensive. Microbial degradation processes may be a feasible remedial measure depending on the extent of oil contamination (Vanloocke *et al.* 1975).

High industrial production can lead to the overuse of groundwater. Declining groundwater levels increases the cost of groundwater withdrawal and may lead to adverse impacts such as base flow reduction, land subsidence, groundwater quality deterioration, seawater intrusion, and contribute to desertification in arid regions (Zektser *et al.* 2005; Wada *et al.* 2010; Dong *et al.* 2014; Famiglietti 2014; Shi *et al.* 2009).

The urban sector

About 96% of the unfrozen fresh water available globally for human consumption is in the form of groundwater; and 50% of drinking water is groundwater (Smith *et al.* 2016). Groundwater withdrawal may exceed its recharge rate, a condition that causes groundwater overdraft when maintained over long periods of time, say, two or more decades (Loáiciga 2017), which is commonly associated with adverse effects such as increased cost of groundwater extraction, depletion of groundwater storage, reduction of base flow, land subsidence, groundwater quality deterioration, and contributes to desertification in some instances.

About 70% of groundwater abstraction worldwide is devoted to irrigated agriculture (Rajeevan & Mishra 2020). It is possible to reduce groundwater withdrawal by using treated municipal wastewater to irrigate agricultural land (Loáiciga 2015). Yadav *et al.* (2002) evaluated the impact of domestic sewage on soil and plants in the state of Haryana, India. Their results established that the amount of heavy metals in the crops sampled from the area was below the critical level. Therefore, efficient use of such domestic sewage may expand the water sources for irrigation. However, some toxic metals such as Ni, Cd, and Pb may accumulate in the plant tissue, and NO_3 may pollute wells, which calls for monitoring and proper treatment of sewage before its reuse.

The metropolitan city of Taejon, Korea, is highly dependent on groundwater, which is threatened by pervasive pollution. Jeong (2001) studied the chemical properties and pollution of groundwater in relation to land use in Taejon. An attempt was made to distinguish anthropological inputs from the effect of natural chemical weathering on the chemical composition of groundwater, leading to the conclusion that most groundwater in the study region is weakly acidic, and that groundwater chemistry is determined mainly by land use and urbanization than the type of aquifer rocks. Jeong (2001) also established that the sources of excess nitrate, chlorine, and CO_2 in groundwater may be leaks in the sewage system, old latrines, and municipal waste at landfills.

FUTURE DIRECTIONS OF THE WEF NEXUS RESEARCH

Most of the analysis and management proposed for the WEF nexus is at a theoretical stage, although current needs call for systematic management more than ever. Solutions emphasizing the importance of having a water, food, and energy-based approach to political and governmental decision-making remain elusive.

The Earth itself is a general dynamic system comprising the WEF nexus. It is timely to develop internationally harmonized WEF nexus methodologies to tackle large-scale comprehensive management of the world's water, energy, and food resources.

Improvement of the performance of WEF nexus management in the environmental field must focus on soil pollution in the future, since soil contamination affects agricultural production and contaminates water in aquifers, which is difficult to treat or remediate. Hatfield *et al.* (2017) argued that soil is an integral part of water, food, and energy resources, and stated that soil is central to food security and energy supply, and even though scientists have studied it well, its impact on political decisions has not yet been felt, which calls for linking studies of erosion and reduction in soil fertility. In

Table 3 | Summary of methods for assessing the environmental impact of the water, energy, and food nexus

References	Region	Environmental aspects	Methodology	Solution
Khan *et al.* (2009)	Australia	Reducing environmental footprints of water and energy	Assessing the data published in journals	Finding two ways to reducing environmental footprints: water productivity and improving energy use efficiency in crop production
Horowitz & Gottlieb (2010)	–	GHG emissions in the agricultural sector	Discussing agricultural sector to investigate GHG emissions	Changing animal feed, installing solar panels or wind turbines in farms
Kumar & Saroj (2014)	Delhi, India	Water pollution, transportation sector accounts for most of health-threatening emissions	Applied integrated approaches for water, energy and pollution nexus, and employed a three-step nexus approach, i.e., water–energy nexus, energy-pollution nexus, and water–energy–pollution nexus	Recommended using 'greener' fuel for power plants and transportation to reduce GHGs and health-threatening emissions, and demonstrated that the water–energy–pollution nexus is useful in decreasing negative impacts on water and air quality in the urban sector
Nair *et al.* (2014)	USA, UK, and Australia	GHG emissions	Employing the water–energy–GHG nexus in urban water systems	Authors reported that suitable nexus methodology is not applied in various systems and regions
Rasul (2014)	Hindu Kush Himalayan (HKH)	The role of ecosystem services in food conservation, water and energy security	Using secondary data from various food, water and energy sources from a regional perspective, the role of Hindu Kush Himalayan (HKH) ecosystem services in food sustainability, water and energy security downstream was emphasized	Cooperation and coordination of food, water, and energy uses cannot be optimally managed unless a basin-level approach is taken
Conway *et al.* (2015)	Southern Africa	Climate perspective	The WEF nexus was used to identify the role of climate and its relationship to the nexus	Enhancing three important political and economic tools (the Southern African Development Community, the Southern African Power Pool and trade of agricultural products amounting to significant transfers of embedded or virtual water)
Al-Ansari *et al.* (2016)	–	Adverse environmental impacts (waste discharge to the environment and CO_2 emissions)	The WEF nexus with novel waste management techniques	Take the form of biomass integrated gasification combined cycle (BIGCC). Apply carbon capture (CC) subsystem for the capture and recycling of CO_2 from combined cycle gas turbine plant (CCGT) and BIGCC.
Karatayev *et al.* (2017)	Kazakhstan	Impacts of the industrial sector on the environment	Identifying key components in agricultural systems necessary for nexus approach to management of natural resources; data analysis	Use data considering important factors (future technology, climate change, transboundary water); Consider future scenarios in agriculture about water use in irrigation

(*continued*)

Table 3 | continued

References	Region	Environmental aspects	Methodology	Solution
Scanlon *et al.* (2017)	–	Improve environmental sustainability	Describe methods to manage resources conflicts	Discussing the importance of quantifying different WEF nexus components
Terrapon-Pfaff *et al.* (2018)	–	Negative effects on the environment of energy use	Study WEF nexus at a local level	Use of renewable sources
Yang *et al.* (2018)	Niger River basin	Threaten basin ecosystem by increasing water, energy, and food demands	Introduce generic metrics to analyze availability of water; Explain coupled ABM-SWAT modeling framework	Need of trade-off analysis among different sectors; Development of dams to reduce negative impacts of climate change on hydropower production and ecosystem health
Markantonis *et al.* (2019)	Mediterranean	Water pollution, Waste food, Water scarcity	Analyzing specific economic options, policy setting and institutional arrangements to reach economic growth	Requires a set of interventions to strengthen the institutional capacities, to enhance the finance mechanisms, to support the intra-regional dialog
Fabiani *et al.* (2020)	Central Italy under Mediterranean conditions	Environmental sustainability (Groundwater quality)	Comparison between agricultural production with mineral fertilizer and organic fertilizer at the farm level to achieve sustainable agricultural management	Reducing groundwater pollution due to the use of organic fertilizers

spite of scientific advances, humanity has not yet found a way to compensate for the loss of soil.

Other issues that would lead to more effective policy making through the WEF nexus approach include addressing water, food, energy, and the environment from social and economic viewpoints, because pollution reduction leads to social and economic prosperity.

Strategies to reduce the harmful effects on the environment rely on improving the WEF nexus and on balancing consumption and resources through sound policy implementation. Therefore, taking into account the environmental impacts (pollution of water, air, and soil) of the WEF nexus would lead to better decision making. For example, coping with the environmental impacts of using fossil fuels calls for a transition to clean and renewable energy sources, which, besides helping to maintain environmental sustainability, would reduce the demands on water, food, and energy resources to meet the needs of growing populations. Also, it is recommended that the analysis of the WEF nexus considers multiple spatial scales, i.e., local, regional, national, and global according to specific conditions.

CONCLUSION

The achievement of environmental, social, and economic sustainability presupposes the understanding of the complex relations between water, food, and energy resources. Several authors have presented numerous interdisciplinary and specialized frameworks and approaches to achieve a dynamic and optimal balance of production and resource utilization in search of resource sustainability. It is in this realm that the WEF nexus approach performs well in achieving sound decisions, policy making, and management by simultaneously examining the relations that exist between the agricultural, industrial, and urban sectors.

The realization that water, energy, and food, directly and indirectly, impact each other calls for cross-sectorial studies of the WEF nexus. Our review of the pertinent literature showed the WEF nexus has been approached in various ways. The interdisciplinary WEF nexus must fully address the interactions between water, energy, and food. For example, climate change has a significant impact on forecasts related to the status and the interplay of water, energy, and food, which in turn affect the climate. There have been many studies of climate change; yet, its extent and range of impacts and predictions in the context of the WEF nexus have not been comprehensively addressed.

An overview of the literature on the WEF nexus from an environmental sustainability perspective was herein presented with respect to the agricultural, industrial, and urban sectors. The review shows that studies dealing with the environmental sustainability in the industrial subsystem rarely take into account the complexity of the relations between the WEF resources, and are generally limited to a binary combination of these three components (water and energy or food and energy, for instance). Table 3 summarizes the research conducted to investigate the environmental impacts associated with the WEF nexus. Many studies have shown that water use by agriculture, industry, and residential sectors causes adverse environmental impacts; yet, in most parts of the world, coordination between the WEF nexus and environmental protection is inadequate. A key finding of this research is identifying the replacement of fossil fuels with renewable fuels as an essential measure to control modern climate change. So is applying integrated water, food, and energy policies.

This work has highlighted the discharge of pollutants that is associated with the WEF nexus and accelerate current climate change. Pollutants that affect human health and the health of other organisms have not been comprehensively analyzed, even though they have a key role in environmental policy making. It is herein recommended that future research consider the feedbacks between resources and their use by the agricultural, industrial, and urban sectors to quantify future patterns of environmental quality and human well-being.

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CONFLICT OF INTERESTS

None.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper.

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