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Water-energy-food-ecosystem nexus in India—A review of relevant studies, policies, and programmes

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Current approaches for utilization of resources in water-energy-food-ecosystem (WEFE) sectors appear to be unsustainable and sub-optimal because of silo-based approaches that ignore interconnectedness across these interdependent sectors. A nexus approach that considers the interactions and interdependence among the sectors helps overcome weaknesses of silo-based approaches to better address synergies and trade-offs. This paper discusses the concept of the WEFE nexus-based approach for achieving water, energy, food, and environment security in India and presents a review of recent relevant literature. The paper critically reviews the key Indian government policies and programmes in the WEFE sector to assess the synergies and trade-offs among them. More than ≈ 40 programmes across WEFE sectors were studied to understand the efforts underway in these sectors to attain the respective policy goals. Although the implementation of the nexus concept will depend upon the enabling government policies and programmes, we find that discussions on these aspects are missing in the literature. Our review shows that the policies of different sectors give inadequate consideration to the impacts of decisions on the other related sectors. Although the various programmes are appreciably contributing to the policy goals and security for respective sectors, there are significant overlaps among the programmes which could positively or negatively impact other sector(s). There is a need to quantify the trade-offs by using an integrated approach including modeling with the WEFE nexus lens. The study also discusses the key challenges and barriers in implementing the nexus concept in India and how to overcome them.

KEYWORDS

water, energy, food, ecosystem, nexus, trade-off, policy, India

1. Introduction

The water-energy-food-ecosystem (WEFE) nexus is a concept that refers to the interconnectedness of these four elements and how they affect each other (FAO, 2014; UNECE, 2022). According to the Merriam-Webster dictionary, the word "nexus" came into English in the 17th century and at that time, it meant "connection" or "link." In recent times in the scientific literature, this word has taken a new meaning, denoting interconnection and interdependencies in the management of resources. In resource management area, nexus was promoted by The World Economic Forum (WEF, 2011) and the Bonn 2011 Conference on "Water Energy and Food Security." The conference highlighted the need to address security and sustainability issues in the interconnected WEF sectors and the need for an integrative approach (Leese and Meisch, 2015).

Water, food, and energy are all essential for human survival and economic development, and the health of our ecosystems plays a critical role in maintaining the availability and sustainability of these resources. The need for nexus approach for planning and utilization of resources arises due to a number of reasons including optimum use of limited resources. We argue and other studies have also highlighted that the management of water, energy and food has immense dependence on environment, it is helpful to extend WEF nexus to WEFE (water-energy-food-environment) nexus (Anandhi et al., 2022).

The WEFE nexus emphasizes the importance of considering the interdependence of these four elements and the need for integrated, holistic approaches to managing them to optimize equitable economic and social welfare and environmental sustainability. In absence of such understanding, resources are being used in manner and quantities that can't be sustained. For instance, Rockström et al. (2009) have demonstrated that humanity has crossed the planetary boundaries in the use of many natural resources. An approach which holistically considers the use of these resources would detect the "disbalance" in the resource use early on. The nexus approach is advocated as it can break down institutional silos and facilitates sustainable, equitable and adaptive governance of resources by accounting for WEFE nexus synergies and tradeoffs (Hoff, 2011; Bach et al., 2012; Belinskij, 2015).

Figure 1 gives a conceptual view of the WEFE Nexus. It shows that there are interconnections and interdependencies among these four sectors which means that the actions taken for utilization or management of the resource in one of these sectors are likely to impact the other sectors at various spatial and temporal scales. We note that in addition to these four sectors, several more facets of society are impacted by the actions in these sectors.

1.1. Tradeoffs in WEFE sectors

The availability of water, food, energy, and environmental resources varies considerably across regions. Given that WEFE sectors have many interconnections and interdependencies, decisions taken in the policy space of one of these sectors have externalities (positive or negative) on the other sectors. For example, water availability and uses impact the options for energy generation, food production, the state of the ecosystem, and also the society in multiple ways (Alam et al., 2022). However, in many cases, almost the entire river flow in the lean season is diverted to irrigate farms, leaving little flow in the river. Consequently, the health of the river ecosystem begins to deteriorate, limiting its ability to provide ecosystem services. Similarly, while the use of groundwater for irrigation has helped attain self-sufficiency in the food sector in many countries, especially in South Asia (Sikka et al., 2020), this has placed a high burden on energy utilities as electricity is provided almost free or at highly subsidized rates. In turn, this is leading to overexploitation of groundwater which is detrimental to water, energy, and ecosystem sectors. Declining water tables are also resulting in contamination of groundwater and associated health problems, besides degradation of ecosystems. It is a considered view that if the decisions in WEFE sectors had considered the inter-linkages and inter-dependencies, goals of developments would have been achieved in a better way and many ills could have been avoided.

Two types of trade-offs can arise in the WEFE nexus: Intra-sector trade-offs, and Inter-sector trade-offs. Inter-sector tradeoff arises from resource use in one sector and has implications for the use of resources in the same sector. For example, when water, which is a finite resource, is captured in upstream its availability in downstream areas may be reduced. Intra-sector trade-offs arise when the decision in a given sector impacts the availability of the resource for the other sectors. For example, when water is used to meet consumptive demands, its availability for other uses is reduced. Likewise, if the quality of water deteriorates due to the discharge of untreated waste by industries, it will harm the environment and bio-diversity, agriculture production will suffer, and more energy would be required to treat water. The trade-offs between water use for domestic, industrial, agricultural, energy, recreation, and environment vary with location, the type of economy, and the development status of the society. Table 1 gives some other examples of the WEFE nexus.

Given the potential synergies and trade-offs in the WEFE sector, there is a need for a holistic and integrated approach to manage WEFE resources. The overall objective of the paper is to assess synergies and trade-off across existing WEFE policies and programs of the government of India. Toward this, this paper briefly discusses the concepts of security in the water, food, energy, and environment sectors and their status in India. This is followed by review of recent relevant WEFE literature to provide an overview of current state of knowledge on the WEFE nexus. Finally, the paper presents an exhaustive compilation and review of policies and programmes of the Govt. of India in WEFE sectors and assess the synergies and trade-offs among them. Finally, it discusses trade-offs, challenges, and barriers in implementing nexus concept, particularly in India and suggests ways to overcome them.

2. Materials and methods

To assess the synergies and tradeoff across WEFE nexus policies and programmes in India, the relevant policies and programs of the Government of India have been compiled and reviewed. This review focuses only on government policies and programmes as described in documents in public domain. To that end, details of relevant Indian government policies (Table 2) and programs (Tables 3–6) related to WEFE were collected, analyzed, and summarized with a view to understand and explain their benefits, contribution, and impact with a nexus lens. For each program, a qualitative impact on WEFE is assessed to show the interdependencies of the WEFE sector. Review of policies and programs is carried out to assess whether these are compliant with the nexus concept and if not then in what ways these can be modified to make them nexus compliant. In the end, recommendations for future research and implementation of WEFE concept have been given. The methodology and flow of the work in this paper is shown in Figure 2.

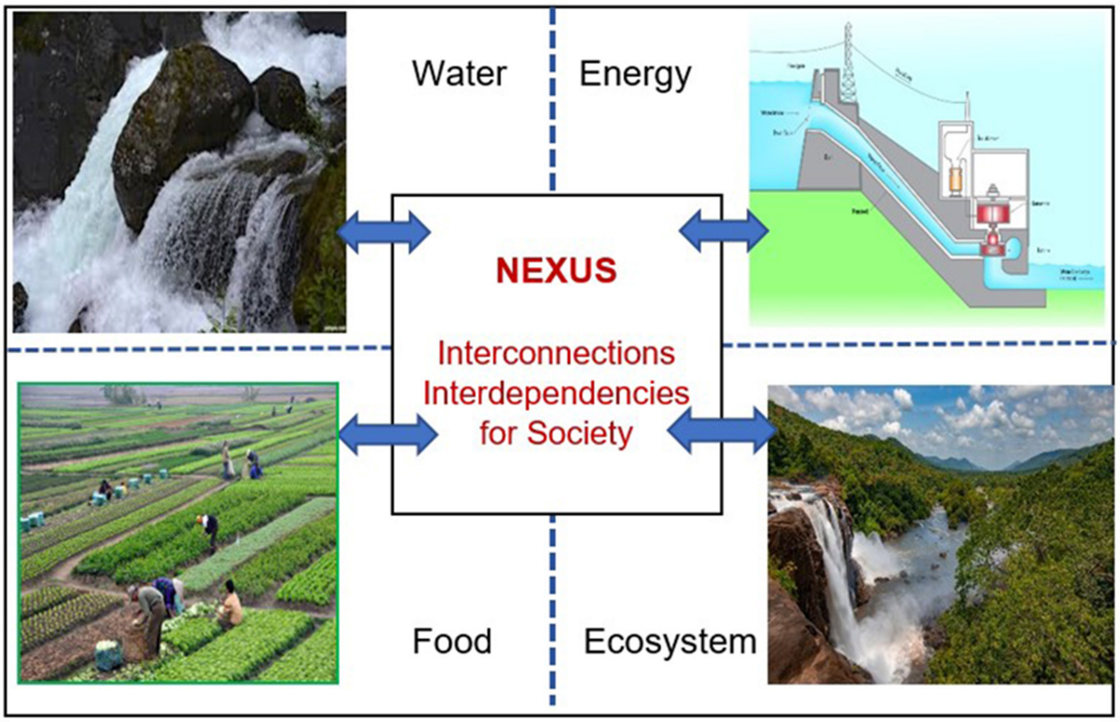

FIGURE 1
A conceptual view of the WEFE Nexus.

TABLE 1 Examples of WEFE nexus tradeoffs and synergies.

Linkages	Examples
Water <-> Food	• Water use for food production: In many developing countries (e.g., India, Bangladesh), around 80 to 90% of water is consumed for food production. This implies that water insecurity (drought) is the most common cause of severe food shortages in developing countries. • High use of water for food production reduces water availability for other needs.
Water <-> Energy	• Water use for energy production: Global water use for energy production is estimated at approximately 52 BCM of fresh water (Spang et al., 2014). Energy production by oil and gas requires the largest amount of water whereas renewables require the least. • Energy is required for pumping, treating and transporting water. • As the demands for energy rise, water requirement for energy generation would also rise, adversely impacting water security, food security (water for irrigation) and the environment (river flows, waste).
Water <-> Environment	• Leonardo da Vinci had termed water as the driver of nature. Water is an essential input for all vegetation growth and hence also for all ecosystem services and associated livelihoods. • Environment defines the upper limit of water available in a region. • Agricultural practices, such as irrigation, can impact the availability of water for other uses and can also affect ecosystems. • Water use for societal needs limits e-flows in rivers. In many places huge quantities of water are diverted for societal needs, leaving little or no water for the needs of the ecosystem. • Health of ecosystems, such as forests and wetlands, can affect the availability of water and food. For example, forests help to regulate water flow and protect water sources.
Food <-> Energy	• In the food sector, energy is used to pump groundwater, supply irrigation water through sprinklers, for operation of farm machinery, for food processing, etc. • The production of biofuels, such as corn-based ethanol, can compete with food production and land resources.
Food <-> Environment	• Intensification of agriculture (including expansion of agriculture area) have negative impacts on ecosystems' example, fertilizers and pesticides/insecticides used to produce food pollute the environment and harm ecosystem security. • Healthy ecosystems (e.g., clean water, healthy soils, pollination) are critical for productive agriculture and nutritious food.
Energy <-> Environment	• Energy generation requires water; it may also degrade the quality of water • The use of fossil fuels for energy production can lead to water pollution and depletion of water resources.

TABLE 2 Summary of key Indian policies in water, energy, food, and ecosystem sector in India.

Policy	Year of declaration/ enactment	Key points	Source
National Water Policy	2012	• Planning, development, and management of water resources need to be governed by national perspectives on integrated and environmentally sound basis. • River basins should be considered as the basic unit for planning. • Integrated water resource management should be the main principle for planning, development, and management of water resources. • Access to safe and clean drinking water and sanitation should be regarded as a right to life essential to the full enjoyment of life and all other human rights.	MoWR (2012)
Energy policy (draft)	2017	• Aims at providing energy security to the people which includes clean energy at affordable prices. • Four key objectives of the energy policy: Access at affordable prices, Improved security and Independence, Greater Sustainability and Economic Growth. • 100% electrification and clean cooking coverage by 2022 • Cumulative capacity target for renewables of 175 GW has been declared for the year 2022; likely capacity of 597–710 GW is expected to be achieved by 2040.	NITI Aayog (2017)
National Agriculture Policy (NAP)	2004	• An agriculture sector growth rate exceeding 4 % per annum; • Make efficient use of resources and conserves our soil, water and bio-diversity; • Growth with equality, i.e., growth which is widespread across regions and famers; • Growth that is sustainable technologically, environmentally and economically.	DAC&FW (2004a)
Ecosystem policy - Ecosystem protection act of 2006	2006	• A set of acts, guidelines, and notices to promote equitable and sustainable development of natural resources while protecting the environment.	MoEF&CC (2022)
National Biological Diversity Policy 2002	2002	• To regulate access to biological resources of the country and equitable share in benefits arising out of the use of biological resources; • To conserve and sustainable use of biological diversity; • To secure sharing of benefits with local people as conservers of biological resources and holders of knowledge and information relating to the use of biological resources; • Protection and rehabilitation of threatened species.	National Biodiversity Authority (2004)
National Agroforestry Policy 2014 (NAP)	2014	• Bringing coordination, convergence, and synergy among various elements of agroforestry; • Improving the productivity, employment, income, and livelihood opportunities of rural households, especially of the smallholder farmers through agroforestry; • Meeting the ever-increasing demand of timber, food, fuel, fodder, fertilizer, fiber, and other agroforestry products; conserving the natural resources and forest; protecting the environment and providing environmental security; and increasing the forest/tree cover, there is a need to increase the availability of these from outside the natural forests.	DoA&C (2014)
National Forest Policy	1988	• The national goal should be to have a minimum of one-third of the total land area of the country under forest or tree cover; • Ensure environmental stability and maintenance of ecological balance including atmospheric equilibrium which is vital for the sustenance of all lifeforms, human, animal and plant.	MoE&F (1988)

3. Overview of WEFE security concepts and status in India

This section provides an overview of the concept of WEFE security and their status in India.

The provision of water, food, energy, and ecological security in India has considerably improved in the past few decades. Unfortunately, in the attempts to provide water, food, and energy security through sector approach, there has been trade-offs and due attention has not been given to the ecosystems. As a result, ecosystems at many places have suffered and the use of natural resources has not always been sustainable. This is becoming more apparent in recent times. For example, in the current year 2023, many places in Himalayan belt and the adjoining areas have seen devastating floods in the summer monsoon season and devastation to infrastructure. This was undermined by rampant development ignoring the environment.

In recent times, in addition to scarcity of water, WEFE sectors are facing growing insecurity due to excess of water. Frequent occurrences of widespread rainfalls with intensities exceeding 80 to 100 mm/day on fragile hillslopes and adjoining areas have forced the planners to reconsider paradigms of land, vegetation and infrastructure management and insecurity arising in WEFE sectors.

3.1. Water security

Water security is the capacity of a population to safeguard sustainable access to adequate quantities of water of acceptable quality for sustaining livelihoods, human wellbeing, and socio-economic development (UN Water, 2013). Water security also requires that protection be provided against water-borne pollution and water-triggered disasters. Rockström et al. (2009) proposed a framework based on “planetary boundaries” and defined safe

TABLE 3 Impact of various water sector policies/programmes on components of WEFE nexus (notation: ↑ (positive), ↓ (negative), ↔ (neutral or unknown).

SN	Policy/program	Water		Energy security	Food security	Ecosystem security	Remarks
		Supply	Demand				
1	Pradhan Mantri Krishi Sinchayee Yojana (PMKSY)	↑	↑	↓	↑	↓	Expanding irrigation coverage will increase food production. Efficient water use would be good for all components—will lead to reduced demand of water. More irrigation will need more energy.
2	Atal Bhujal Yojana (ABY)	↑	↑	↑	↑	↔	Sustainable groundwater management will positively impact water supply and demand, reduce the energy use of irrigation, limit the impact on future food production from depleting resources, and provide more water for environmental needs (e.g., baseflows)
3	National Project on Aquifer Management (NAQUIM)	↑	↑	↓	↑	↓	
4	Namami Gange Programme	↔	↔	↔	↑	↑	Improved river quality will have positive externalities for agriculture and environment.
5	Interlinking of Rivers (ILR)	↑	↑	↔	↑	↑↓	ILR will help overcome water demand supply mismatch and generate additional energy. Depending on implementation, ILR can have both negative and positive externalities for ecosystem.
6	National Water Mission (NWM) and Bureau of Water Use Efficiency (BWUE)	↑	↑	↔	↑	↑	Intervention on supply and efficiency will help increase supply and reduce demand. Efficient use of water will be good for all nexus components
7	Jal Jeevan Mission (JJM)	↑	↑	↓	↔	↓	This will increase supply for providing water security to households, may increase demand and competition for water with other uses (agriculture and environment)
8	Springs and their rejuvenation	↑	↑	↔	↑	↑	Large mountain population depends on springs for their water needs. Many springs and dying and their rejuvenation will contribute to almost all nexus components
9	Dam Rehabilitation and Improvement Programme	↑	↔	↑	↑	↑	Better water supply, energy generation, and food production.
10	Flood management and border areas programme (FMBAP)	↔	↔	↔	↑	↑	More energy and food production, and ecosystem security
11	Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS)	↑	↔	↔	↑	↑	Interventions, mostly, on supply side will increase water available for irrigation. However, it may marginally reduce flows for other users.
12	Central Ground Water Authority (CGWA)	↑	↔	↑	↑	↑	CGWA has been created to regulate groundwater use, particularly in areas with alarming decline in water tables.
13	Water quality Assessment Authority and National River Conservation Directorate (NRCD)	↔	↔	↓	↔	↑	Improved river quality will have positive externalities for agriculture and environment.

TABLE 4 Impact of various agriculture sector policies/programmes on components of WEFE nexus (notation: ↑ (positive), ↓ (negative), ↔ (neutral or unknown).

SN	Program/policy	Water		Energy	Food	Ecosystem security	Remarks
		Supply	Demand				
1	National Food Security Mission	↔	↑	↓	↔	↔	Area and production expansion will increase lead to an increase in water demand and energy for pumping; an increase in productivity and focus on pulses and nutri- cereals may reduce water demand and associated energy use
2	Price support scheme/Minimum support price (MSP)	↔	↑	↔	↑	↓	Continued MSP incentivizes current resource incentive rice-wheat cropping pattern
3	NMSA component: Rainfed Area Development (RAD)	↓	↔	↔	↑	↔	Development and conservation of natural resources along will increase supply, increase productivity
4	NMSA component: Sub-Mission on Agroforestry (SMAF)	↓	↔	↔	↔	↑	More carbon sequestration, will support national initiatives on climate change adaptation and mitigation
5	NMSA component: Soil Health Management	↑	↔	↔	↑	↑	Judicious use of fertilizers, increasing productivity, increase soil storage.
6	Paramparagat Krishi Vikas Yojana (extended component of Soil Health Management Scheme)	↔	↔	↔	↑	↑	Promoting organic farming, resulting in improved soil health.
7	Promotion of Agricultural Mechanization for *in-situ* Management of Crop Residue	↔	↔	↓	↔	↑	Will lead to improved environment with less burning of residue; may require more energy.
8	Sub-Mission on Agricultural Mechanization (SMAM)	↔	↔	↓	↑	↔	More use of machines in agriculture, higher crop produce.
9	National Edible Oil Mission-Oil Palm	↔	↔	↔	↑	↔	increasing the domestic production of edible oils to reduce import, positive implication for food security.
10	Mission for Integrated development of horticulture	↔	↔	↔	↑	↔	Holistic growth of the horticulture sector will results in better food and nutritional security.
11	Sub Mission on Plant Protection and Plant Quarantine (SMPPQ)	↔	↑	↑	↑	↑	Increasing crop productivity will lead to efficient resource use, positive externality of water, energy and environmental conditions. Will results in better food security.
12	Sub-Mission on Seeds and Planting Materials	↔	↑	↑	↑	↑	
13	Rashtriya Krishi Vikas Yojana (RKVY)	↔	↓	↔	↑	↔	Will results in demand reduction, better food security.
14	Fisheries and Dairy	↔	↔	↔	↑	↔	Increase food and nutritional security.

operating space consisting of nine boundaries associated with Earth's biophysical subsystems. Global freshwater use was one of the boundaries. In 2009, global freshwater use was within planetary boundaries. Even though the boundary of global freshwater use is not breached yet, many places are facing water shortages or water-related disasters, compromising water security. Vörösmarty et al. (2010) found that nearly 80% (4.8 billion) of the world's population is exposed to high levels of threat to water security.

India is among one of the most water-stressed countries. In water sector, India has completed several challenging projects to harness water resources and provide water security. For example, the ongoing Jal Jeevan (Water life) Mission has been able to provide tap connection to 96.5 million rural households out of total 192 million households (Department of Drinking Water and Sanitation, 2023). Likewise, open defecation practice has been nearly eliminated in India. However, the pace of project construction has slowed recently and the current quantum of water use in India and its rise is not sustainable. In large parts of the country, the water use equals or exceeds availability. At many places, the annual groundwater withdrawal exceeds the annual recharge, leading to groundwater mining. Using the data from the GRACE satellites, Rodell et al. (2009) had estimated

TABLE 5 Impact of various energy sector policies/programmes on components of WEFE nexus (notation: ↑ (positive), ↓ (negative), ↔ (neutral or unknown).

SN	Policy/program	Water		Energy security	Food security	Ecosystem security	Remarks
		Supply	Demand				
1	Hydro Power and Related Policy Measures	↑	↔	↑	↑	↓	Increase hydropower development have positive implications for energy, water, food (increasing supply) but may adversely impact environment.
2	KUSUM (Kisan Urja Suraksha evam Utthaan Mahabhiyan) Scheme	↔	↔	↑	↔	↑	Increased solar power and solar irrigation will have positive implication for the energy and environment sector. Impact on food and water sector could be both ways. For example, free solar power may increase water abstraction or may compete for land with agriculture.
3	Jawaharlal Nehru National Solar Mission or National Solar Mission (NSM)	↔	↔	↑	↔	↑	
4	Energy use efficiency Bureau of Energy Efficiency (BEE); National Mission for Enhanced Energy Efficiency (NMEEE); National Energy Efficient Agriculture Pumps	↔	↔	↑	↔	↑	Increase energy use efficiency will have positive implications for the energy and environment (reduced emissions) sector.
5	Deen Dayal Upadhyaya Gram JyotiYojana (DDUGJY): Separation of agriculture and non-agriculture feeders	↔	↔	↑	↑	↔	Similar scheme of separation of agriculture and non-agriculture feeders has been very successful in Gujarat. It will help control wasteful use of electricity and rapid decline of ground water tables.

huge depletion of groundwater in northwest India. The latest assessment shows that almost a quarter of assessed units have unsustainable groundwater extraction (CGWB, 2022). Further, about half of country's agricultural area is rainfed (DoA&FW, 2022) and thus there is need to expand irrigation which may further strain the resources. To some extent, food and energy can be imported but not water and environment. Water also connects the food, energy, and environment, and many other sectors such as social, economic, and cultural. Detailed data pertaining to Indian water sector is available in Jain et al. (2007).

Some key causes adversely influencing water security in India are: (1) skewed distribution of water availability—spatial and temporal, leading to floods and droughts; (2) Widespread dwindling of water quantity and degrading quality of raw water sources; (3) Unsustainable and unregulated surface and groundwater exploitation (too much dependence on groundwater and falling water tables are a concern in providing water security); (4) India is vulnerable to a large number of climate-related natural disasters, such as floods, droughts, cyclones, and river erosion. (5) Socio-economic changes (e.g., increasing population, urbanization, competing sectoral demands); (6) Widespread pollution of water bodies and ecosystem degradation; (7) Fragmented governance and data scarcity, and (8) Adverse impact of climate change, exacerbating the weather extremes.

3.2. Food security

According to 2009 declaration of the World Summit on Food Security World Summit on Food Security (2009), food security arises when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food. The food should be according to the preferences and needs of the people. Food security has four pillars: food availability, physical and economic access to food, stability of supply and access, and food utilization (CFS, 2014).

India currently produces enough food grains that make it self-sufficient with production estimated to be 308.65 million tons for 2020–21 (DoA&FW, 2022). A wide variety of crops are grown in India and the production of many food grains, pulses, fruits, milk, etc. has increased many folds over the past few decades. Today, India is one of the major producer and exporters of several agricultural products. India is the largest producer, consumer, and importer of pulses in the world. Also, India is the largest producer of milk, jute and pulses, and the second-largest producer of rice, wheat, sugarcane, cotton and groundnuts, as well as the second-largest fruit and vegetable producer (FAO, 2023). However, access to food and affordability of a balanced and nutritional diet is a concern, with about 15% of the population estimated to be undernourished in the period 2015–17 (FAO, 2018). Increasing population and demographic changes will require production to substantially increase by 2050. India ranked 68 out of 113

TABLE 6 Impact of various environmental sector policies/programmes on components of WEFE notation: ↑ (positive), ↓ (negative), ↔ (neutral or unknown).

SN	Program/policy	Water		Energy	Food	Ecosystem security	Remarks
		Supply	Demand				
1	National Mission on Sustainable Habitat (NMSH)	↔	↔	↔	↔	↑	Promotion of sustainable habitats (Reducing GHGs, resilient cities, rejuvenations of water bodies green spaces) will have positive implications for the ecosystems.
2	National Mission for Sustaining the Himalayan Ecosystem (NMSHE) and National Mission on Strategic Knowledge for Climate Change (NMSKCC) and state action plan on climate change (SAPCC)	↔	↔	↑	↔	↑	Various tasks and knowledge generated will help in sustainable use of natural resources in the Himalayas and building resilience to climate change.
3	National Mission for a Green India (NMGI)	↔	↔	↑	↔	↑	Forests provide a wide range of ecosystem services (e.g., fuel and fiber, clean air, filter water supplies, control floods and erosion).
4	Environmental Appraisal of River Valley Projects	↔	↔	↑	↑	↔	Scientific appraisal of river valley projects is carried out by following the provisions of notification promulgated by the Ministry of Environment, Forest and Climate Change ("MoEFCC") in 2006 (http://www.environmentwb.gov.in/pdf/EIA%20Notification,%202006.pdf). In appraisal, all relevant information about a project or activity is scrutinized to assess its potential adverse impacts on the ecology of a region. This exercise is resulting in better and eco-friendly harnessing of natural resources.
5	State Action Plans on Climate Change (SAPCC)	↑	↑	↑	↑	↑	If the State Governments make and implement adaptation plans to manage impacts of climate change, it will results in better security in WEFE sectors.

EIA/EMP/SIA, Environmental Impact Assessment, Environmental Management Plan, Social Impact Assessment.

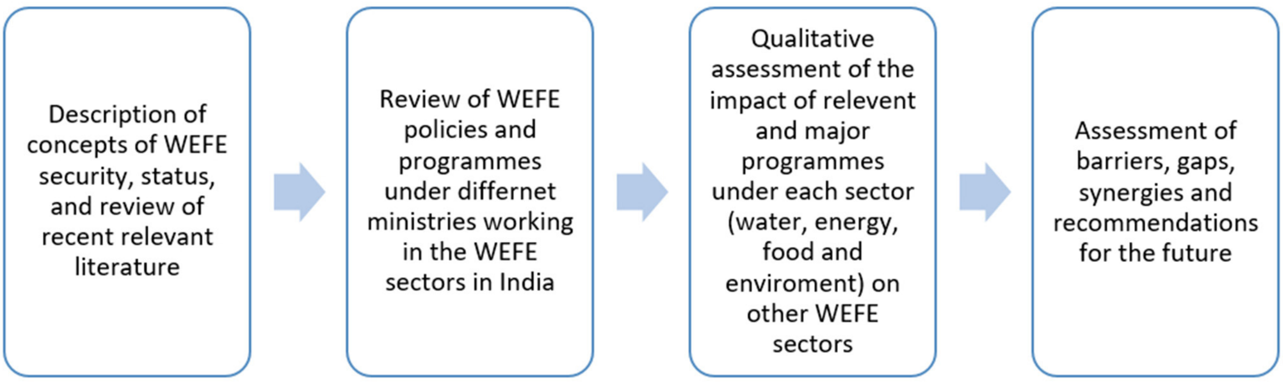

FIGURE 2
The methodology and flow of the work followed in this paper.

countries on the global food security Index lagging much behind in affordability, quality, and sustainability (The Economist, 2022).

Attempts to provide food security to growing population by massive expansion in agriculture area has a concern that it is likely to harm water and environment. Also, as opined by WEF (2011), agricultural sector, particularly in developing countries, works with old technology, lesser mechanization, and weak institutions. Strong farmer lobbies often constrain the decision space. In addition, as noted by IPCC (2019), climate change, including increases in frequency and intensity of extremes, has adversely impacted food security and terrestrial ecosystems.

In view of increased climate variability, aridity, plant diseases, and limited technological improvements in agriculture yields, higher demand for food, water, and more resource intensive consumption and production would result in higher risks from water scarcity in drylands, land degradation, and food insecurity (IPCC, 2019). Many climate change adaptation and mitigation practices can also combat land degradation, soil fertility management, and enhance food security.

3.3. Energy security

Energy security is the uninterrupted availability of energy sources to a country or a region at an affordable price (IEA, 2022). Energy security is important at two-time horizons: long and short-term. Long-term energy security is necessary for the supply of energy for economic development and the ecosystem. Short-term energy security requires that the energy production systems can supply energy as per the short-term fluctuations in demand.

India has made huge strides in increasing electricity generation; installed capacity was 417 GW (May 2023) against 245 GW (March 2014). In 2022, 60% of installed capacity from fossil fuel (coal/gas, etc.) and ∼ 40% from non-fossil fuel (Renewable Energy + Nuclear) (Ministry of Power, 2022). India has also achieved a nearly 100% connection rate for all its willing households but providing reliable power of adequate quality on regular basis remains an ongoing and evolving challenge (Bali et al., 2020). Currently, the focus is on increasing the electricity generation from renewable sources (Solar, Wind, Hydro, and Biopower) as India under its Nationally Determined Contributions (NDCs) has committed to reduce the emission intensity of its GDP by 45% by 2030 compared to the 2005 level (Government of India, 2022). Overall generation from renewables has increased drastically with renewable installed capacity being 152 GW and 78 GW under installation (Ministry of Power, 2022). Additionally, population, economic and demographic change means that by 2047 the energy demand of India is likely to go up by 2.7–3.2 times between 2012 and 2040, with the electricity component itself rising 4.5-fold (NITI Aayog, 2017).

Around 35 billion cubic meters (BCM) of water was withdrawn in India for energy-related purposes in 2016. Around 40% of thermal (mostly coal-based) power plants in India are situated in high-water-stress areas (Rakitskaya, 2021). Due to water shortages between 2013 and 2016, 14 largest thermal power stations in India faced shutdowns. Recent experience in Covid times and the Ukraine war has shown how unexpected turn of events can be detrimental to a nation's food and energy securities. WEF (2011) had projected that by 2030, hydropower will become the dominant renewable energy source. However, water evaporated from hydropower reservoirs will also increase substantially since 17 m^3 of water is evaporated per MW-hour power produced compared to 07 to 2.7 m^3 per MW-hour power produced in thermal plants. In 2022, World meteorological organization (WMO) annual report on state of climate services (WMO, 2022) warned that the supply of electricity from clean energy sources must double within the next 8 years to limit global temperature increase. Otherwise, there is a risk that climate change, more extreme weather and water stress will undermine our energy security and even jeopardize renewable energy supplies.

3.4. Ecosystem security

Ecosystem security is a subcategory of the broader concept of human security. The human Development Report 1994 by United Nations Development Programme (UNDP, 1994) identified environmental security together with food, health, personal, community, economic, and political security as the key components of human security. Ecosystem security comprises compliance, conservation, pollution prevention, restoration, and application of environmental security technology. It denotes the state of protection of the natural environment of a region from the threats arising from human and natural impacts on the environment (Zurlini and Muller, 2008). Müller et al. (2008) opined that the growing knowledge about environmental change, stress, and degradation has led the people to realize that the environmental conditions are important determinant of security in WEF sectors. This is truer since new political, economic, social, and environmental challenges have emerged in recent times.

Ecosystems provide freshwater, food, and energy, and other resources. However, in providing these, environment suffers and degrades when one or more these take place: too much water is consumed/diverted, partially or un-treated solid/liquid wastes are dumped in ecosystems, bio-diversity is harmed, and deforestation takes place. Already approximately 3 billion people live in areas that are land degradation hotspots, jeopardizing food and water security (Ratner, 2018). Hence, these systems should be analyzed and managed in an integrative manner, taking due consideration of the structural and process-based linkages (Zurlini and Muller, 2008). A nexus-based approach to ecosystem management should attempt to reduce the damage to the goods and services upon which society depends and should support their restoration.

In India, rapid population and industrial growth and urbanization are leading to increased consumption of resources. Degraded ecosystems may be able to provide lesser goods and services and of poor quality and reliability. Specifically, for water, river, and groundwater pollution due to the stated causes has become a serious problem. The Central Pollution Control Board (CPCB, 2022) has classified polluted river stretches (PRS) in five classes on the basis of maximum BOD level observed. Total number of PRS in 2022 was 311; this number was 351 in 2018. In recent decades loss of bio-diversity is also a major concern. For example, the Indo-Burma hotspot has lost 95% of its vegetation area, from 23.73 lakh sq. km to 1.18 lakh sq. km (CSE, 2021). More details have been provided in Annexure A.

Rejuvenation of ecosystems requires water, bio-resources, and energy. Thus, the use of these resources is circulatory—at some places, it follows a vicious cycle and it is a virtuous cycle at other places. Understanding the linkages is helpful in converting a vicious cycle to a virtuous cycle. For this conversion to happen, degradation of ecosystems, pollution, and impacts of climate change will have to be addressed and adequate quantity of water would have to be set aside for ecosystems by assessing and implementing environmental flows (Jain and Kumar, 2014). To accomplish all these tasks, resource management by following the nexus way is necessary.

4. Review of recent literature relevant to WEFE nexus

Multiple researchers have studied the water-energy-food-ecosystem (WEFE) nexus, recognizing its significance in sustainable resource management (Bach et al., 2012; UNESCAP, 2013; Belinskij, 2015; Barik et al., 2017; Lee et al., 2020; Sarkodie and Owusu, 2020; Naidoo et al., 2021; Anandhi et al., 2022). Based on a bibliometric analysis of water-energy-food nexus, Sarkodie and Owusu (2020) reported that research on this WEFE topic is expanding rapidly. For example, in a report by UNESCAP (2013), two case studies, in Central Asia and Mekong basin, were highlighted that explored the various aspects of the WEFE nexus. Report noted that the failure to value water economically and neglecting the allocation of water to ecosystems contribute to the degradation of aquatic ecosystems, as seen in the case of drying of Aral seas, as they are often overlooked in infrastructure investments for water, food, and energy security. Similarly, the Mekong River Basin has experienced rapid economic growth, construction of storage and diversion projects, and expansion of agricultural areas, leading to changes in the natural flow regime of the river. This alteration has adversely affected local populations and poses threats to water, food, energy, and ecosystem security, compounded by climate change and the intrusion of seawater into coastal aquifers. A nexus-based management approach would have identified and addressed these concerns earlier, thereby preventing ecosystem degradation. The Commission on Sustainable Agriculture and Climate Change reviewed the scientific evidence so as to find how to achieve food security in the wake of climate change and gave important recommendations (Beddington et al., 2011). They suggested that the food systems should be modified so that they do not exceed planetary resources and better meet human needs. Some other studies have considered assessment of the water-food-energy nexus in India. Barik et al. (2017) highlighted the changing patterns of consumptions and have suggested measures which could be incorporated for judicious regulation and control. Kholod et al. (2021) provided a review of WEF nexus studies for India. Naidoo et al. (2021) developed a Theory of Change for operationalizing the nexus approach in Southern Africa. We also note that the nexus concept has been used in different studies in very different ways which shows the evolving nature of nexus approach. Some of the studies have focused on one sector of the nexus and then examined its connections/impacts on other sectors. Some studies (e.g., de Amorima et al., 2018) have, of course, adopted a holistic approach to examine how the nexus challenges are dealt with on a river basin or larger scales.

Endo et al. (2015) pointed out that there are no definite methods for WEFE nexus studies. Similar views were expressed by Albrecht et al. (2018). Anandhi et al. (2022) in an effort toward synthesizing existing knowledge on WEF nexus provide a detailed review capturing multiple definitions and conceptualization and provided a framework to operationalize the same for a project by stakeholders.

Despite the increase in studies on WEFE nexus (Sarkodie and Owusu, 2020; Anandhi et al., 2022), the impacts of results on policy are not commensurate because a common conceptual framework is lacking. As a result, implementing the nexus solution encounters several barriers including a sector-based approach resulting in fragmented management, inadequate data for policy formulation and implementation, and governance challenges such as political will, stability, legal frameworks, and transboundary agreements (UNESCAP, 2013). Reviewing the applications of the nexus concepts, Pahl-Wostl et al. (2021) noted that the governance of the WEF nexus has received inadequate attention and the importance of scale in space and time has been largely ignored. They identified four scale-related governance challenges in the WEF nexus; relevance of these challenges was illustrated with case studies from Germany, Cambodia, Laos, Thailand, Vietnam, and Sri Lanka. Also, studies have highlighted the need for incorporating economic, social, and political dimensions for effecting operationalization of nexus approach (Anandhi et al., 2022). Overcoming these barriers requires a shift toward a balanced nexus approach, where core ministries governing water, agriculture, energy, and environment collaborate and develop long-term policies through consultation, supported by comprehensive studies and data analysis.

With increasingly connected WEFE systems, there is a need to identify, assess, prioritize, and scale the most suitable WEFE nexus management intervention. However, governments, stakeholders, and investors struggle to manage system wide changes in the water-energy-food-ecosystems nexus and to ensure that the changes are robust under climate change. One key barrier in the implementation of any Nexus approach to a real-life problem is the lack of enabling policies and programs. While significant investments are being made in WEFE sector these policy/programmes are largely working in silos. The objective of this paper is to provide an overview of water-energy-food-ecosystem policies and programmes in India along with their synergies and tradeoffs. A scan of technical literature in WEFE sector shows that such coverages are typically missing in the literature. The review will highlight the linkages among the programs as well as missing links that need to be addressed to reap synergistic gains among the programs and can provide the template for carrying similar studies in other countries/regions.

5. Review of WEFE policies and programs in India

WEFE security can't be achieved unless enabling policies and programs are in place. Details of relevant Indian government policies (Table 2) and programs (Tables 3–6) related to WEFE were collected, analyzed, and summarized with a view to understand and explain their benefits, contribution and impact with a nexus lens.

WEFE related policies and programs are in the domain of different ministries of the Government of India that work on topics that are related to WEFE nexus, mostly in silos. Some key ministries are the Ministry of Jal Shakti [Water power (MoJS), Ministry of Environment, Forests and Climate Change (MoEF & CC), Ministry of Agriculture & Farmers Welfare (MoA&FW), and Ministry of New and Renewable Energy, Ministry of Coal and Ministry of Power (MoP)]. In addition, there are other ministries such as the Ministry of Earth Sciences (MoES) and Ministry of Food Processing Industries, Ministry of Science and Technology (MoST) that also implement some WEFE policies and programs. Thus, the presence of different ministries working on different aspects of the WEFE sector reflects the importance to this topic as well as the institutional challenges toward operationalizing a coherent and integrated WEFE approach. In addition, as per the constitution of India, several aspects of the WEFE sectors such as water and food are State subjects (which means that the State governments have the main role in their management) or fall in concurrent list (both State and Central government play key roles). Thus, the roles of concerned departments of State Governments, e.g., irrigation/water resources, agriculture, environment, forests, planning, etc. are also very important in WEFE security. Here, we focus our review on national policies and programs that have a large influence on the WEFE sector and on state government programs.

5.1. Water-energy-food-ecosystem policies in India

Ministries of the Government and related organizations have developed and announced policies concerned with their domain area. Water, Energy, and Agriculture policy goals are set in respective water, energy, and agriculture policies (Table 2). Ecosystem, covering a large sphere, is overseen by multiple policies such as the Ecosystem protection act of 2006, the National Biological Diversity Policy 2002, the National Agroforestry Policy of 2014 (NAP), and the National Forest policy to name few. Table 2 summarizes some salient points of these policies.

India declared its first National Water Policy (NWP) in 1987; it was updated in 2002 and then in 2012 (MoWR, 2012). The policy is again under revision. NWP emphasized the importance of an integrated water resource management approach and considering river basin as the basic unit for water management. However, water being a state subject, operationalizing the basin approach has remained a challenge and increasing water demand has meant an increasing frequency of inter-state water conflicts.

India's draft national energy policy (NEP) by NITI Aayog, a think tank of Govt. of India, came in 2017 NITI Aayog (2017). NEP 2017 builds on the earlier Integrated Energy Policy (IEP). Draft National Energy Policy (NEP) has four key objectives in the energy sector: Access at affordable prices, Improved security and Independence, Greater Sustainability, and Economic Growth. NEP has proposed actions to meet the objectives so that India's economy is "energy ready" by the year 2040. India's climate targets are closely intertwined with the energy policy. India's Nationally Determined Contribution (NDC) has set a target to reduce the emissions intensity of its GDP by 45 percent by 2030, from the 2005 level (Government of India, 2022). A significant part of this target is to be achieved by increasing the generation of electric energy from renewable sources.

In India, a large section of society directly or indirectly depends on agriculture. At the national scale, the first National Agriculture Policy (NAP) was announced in 2000 (DAC&FW, 2004b). NAP emphasized the importance to realize the vast untapped potential of Indian Agriculture by strengthening rural infrastructure to support faster agricultural development, promoting value addition, accelerating the growth of agro-business creating employment in rural areas, and securing a better standard of living for the farmers and agricultural workers. However, NAP is old and since agriculture is a state subject, different states have come up with their state agriculture policies. Many subsequent developments had important implications on the agriculture policy landscape in India. For example, National Policy for Farmers (NPF) 2007 emphasized the need to focus more on the economic wellbeing of farmers rather than just production (MoE&F, 1988). The National Food Security Act (2013) marked a paradigm shift in approach to food security with the act legally entitling up to 75% of the rural population and 50% of the urban population to receive subsidized food grains under a targeted public distribution system (DoF&PD, 2022). Other recent initiatives include a focus on doubling farmer income.

The Constitution of India recognizes conservation and protection of the environment as important elements of governance. In accordance, India has a well-developed legal framework for environmental protection. A key landmark in efforts to protect the environment was the Environmental Impact Assessment ("EIA") Notification, promulgated by the Ministry of Environment, Forest and Climate Change ("MoEFCC") in 2006. Among the other things, this notification lays down the process for appraisal of development projects that may impact the environment (MoEF&CC, 2022). India is also a signatory to Convention on Biological Diversity (CBD) treaty (United Nations, 1992) and has enacted the Biological Diversity Act to implement the same (Anandhi et al., 2022). CBD has three objectives—conservation of biological diversity, sustainable use of the diversity, and ensuring fair and equitable sharing of benefits of such use. India's National Agroforestry Policy launched in 2014 is aimed to improve agricultural livelihoods by maximizing agricultural productivity and mitigate climate change. This policy also aims to support the nation attain forest or tree cover over 33% of the area, a target that has been outlined in the National Forest policy (MoE&F, 1988).

5.2. Programs in the water-energy-food-ecosystem sector

Implementation of policies takes place through various means, including programs that are run by governments. A partial list of programs (sector-wise) running in India that Impact WEFE security is reviewed here. We have focused on the main national programs only. For each program, a qualitative impact on WEFE is assessed to show the interdependencies of the WEFE sector. Tables 3–6 provide the list of all potential programs. However, the text only discusses the main programs whereas Table B1 (Annexure B) provides the link to sources for each program.

5.2.1. Programs in the water sector

Table 3 lists 13 main programs in the water sector contributing toward achieving goals set under India's National Water Policy. Different programs focus on a different aspects of water management including supply enhancement, demand management, and water quality. The impacts (positive, negative, and neutral) of various policies/programmes on components of WEFE nexus, as finalized in consultation with some experts/stakeholders, are also shown. It is clear from Table 3 that these schemes have extensive interconnection with other sectors, especially food as agriculture is the largest consumer of water in India. Some of the key programs include Pradhan Mantri Krishi Sinchai Yojana (PMKSY- Prime Minister Agriculture Irrigation Scheme), Atal Bhujal Yojana (Groundwater scheme), Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS), Jal Jeevan Mission (JJM, water-life mission), National Water Mission (NWM), and Namami Gange program (worship Ganga program, focused on Ganga rejuvenation).

The overarching aim of PMKSY is to provide better irrigation water management including its efficient management. Key components of PMKSY include extending the coverage of irrigation to each farm, efficient use of irrigation water (per drop more crop), and accelerated completion of ongoing and delayed major and medium irrigation projects. All activities under PMKSY have strong implications for the WEFE sector. For example, increasing irrigation access will have a positive impact on crop production thus enhancing water and food security. Similarly, efficient irrigation leading to water saving may mean more water for other sectors, including ecosystem and energy. However, the energy required for irrigation may also increase the overall energy requirement and the capture of water for irrigation may reduce water available for the environment. These benefits and trade-offs need to be examined by applying some analytical approach within the WEFE nexus thinking including the use of integrated models.

Atal Bhujal Yojana (ABY) ("Bhujal" is groundwater) is focused on sustainable groundwater management through a community participatory approach. Groundwater provides irrigation to ∼ 63% of irrigated areas but this has led to overexploitation in large parts of the country. Thus ABY, being implemented in 80 selected districts across 7 States in India, aims to manage this unsustainable abstraction of groundwater. This will have a positive implication for all aspects of WEFE. Sustainable resource abstraction will positively impact water supply and demand, reduce the energy use of irrigation, limit the impact on future food production from depleting resources, and provide more water for environmental needs (e.g., baseflows).

MGNREGS, under the Ministry of Rural Development (MoRD), is not a water program directly but is an employment guarantee scheme that aims to enhance livelihood security by providing at least 100 days of wage employment in rural areas to voluntary households. Interestingly, MGNREGS has a special focus on natural resource management with 181 activities (out of 260 specified activities) related to natural resource management (84 activities are directly related to water). This also has important implications for other WEFE sectors as highlighted in Table 3.

Another key program that aims to provide safe and adequate drinking water through individual household tap connections to all households in rural India by 2024 is the Jal Jeevan Mission (JJM). The Namami Gange program aims at effective abatement of pollution and conservation and rejuvenation of Ganga River.

5.2.2. Programs in the food sector

Table 4 lists 14 main programs in the agri-food sector contributing toward goals set under India's agriculture policy and with direct implications on the WEFE sector. Different programs focus on different aspects of food security including increasing food production by enhancing yields (production security), diversification of cropping (nutritional security), and farmer's income enhancement (livelihood security). It is clear from Table 4 that these schemes have extensive interconnection with other sectors, especially water and energy. Some of the key programs include National Mission for Sustainable Agriculture (NMSA), National Food Security Mission (NFSM), Rashtriya Krishi Vikas Yojana (RKVY), the price Support scheme, and organic/natural farming. Some other schemes provide direct economic support which we don't consider here but links to the economy of farmers [e.g., Pradhan Mantri Kisan Samman Nidhi (PM-Kisan); Pradhan Mantri Kisan Man Dhan Yojana; Pradhan Mantri Fasal Bima Yojana; Formation and Promotion of 10,000 Farmer Producer Organizations (FPOs)].

National Food Security Mission (NFSM) was launched in 2007–08 to increase the production of rice, wheat, and pulses through area expansion and productivity enhancement, restoring soil fertility and productivity and enhancing farm-level economy (United Nations, 1992). Under the scheme, various interventions are being implemented through state governments, with a focus on low productivity and high potential districts, for enhancing the production and productivity of food grain crops and commercial crops. The mission aims to provide special emphasis on pulses and nutri-cereals to achieve self-sufficiency in these crops along with nutritional security. This includes targeting rice fallow area in 11 states where post-monsoon cultivation is limited due to water scarcity by promoting the cultivation of pulses in rice fallow areas of the states.

National Mission for Sustainable Agriculture (NMSA) focuses on enhancing agricultural productivity, especially in rainfed areas (DAC&FW, 2019). This is to be achieved through a range of interventions including integrated farming, water use efficiency, soil health management, and synergizing resource conservation. NMSA derives its mandate from the Sustainable Agriculture Mission which is one of the eight Missions outlined under the National Action Plan on Climate Change (NAPCC). There are multiple components of NMSA including Rainfed Area Development (RAD), Sub-Mission on Agroforestry (SMAF), and soil health management (SHM).

All activities under NFSM, NMSA, and other schemes (e.g., Sub-Mission on Agricultural Mechanization, Sub Mission on Plant

Protection and Plant Quarantine, Sub-Mission on Seeds, and Planting Materials) focused on increasing production have strong implications for the WEFE sector. While they all will contribute toward food security, increasing cropping intensity may increase water and energy demand for agriculture. On the other hand, increasing productivity in existing crop areas will lead to more judicious use of resources which will increase the water and energy productivity of agriculture. Also, the focus is on crop diversification by replacing water-intensive crops (e.g., paddy) with pulse and millets (e.g., crop diversification program under RKVY). There is also a recent emphasis on increasing area and production under organic and natural farming [Paramparagat Krishi Vikas Yojana (PKVY)] to reduce the use of chemical fertilizers and pesticides. Thus, increasing productivity and crop diversification to less resource intensive corps may ease pressure on scarce natural resources. Again, these benefits and trade-offs need to be quantified using analytical approach within the WEFE nexus thinking including the use of integrated models.

A key scheme in India, which doesn't directly relate to technology or agronomy measures but has a significant impact on the nation's agriculture is the Price Support Scheme. Under this, the commission for Agricultural Costs and Prices (CACP) recommends a minimum support price (MSP) for 22 crops and a Fair & Remunerative Price (FRP) for sugarcane. The Government also organizes procurement operations of these agricultural commodities through various public and cooperative agencies. Over the long-term MSP for rice and wheat, linked with public procurement of the same for distribution, has led to the intensification (and dominance) of resource-intensive rice-wheat cropping in Northwestern states by discouraging the production of other crops. This has caused widespread natural resources (groundwater, soil) degradation and depletion. Thus, MSP sets a strong economic incentive/disincentive to grow certain crops and significantly impacts other WEFE sectors.

Note that we have looked at agriculture crop production only, but it is important to recognize the fisheries and livestock sectors also contribute significantly to food and nutritional security.

5.2.3. Programs in the energy sector

Energy is inextricably linked to the water, food, and environment sector. Energy is an important input to agriculture (irrigation, land preparation, processing) and water (distribution, treatment). At the same time, water and land are important inputs for energy production and increasing focus on biofuels means a direct trade-off of land for energy and food production. The energy sector is also large with the contribution of different sources of energy (hydro, renewables, coal, nuclear) with different ministries (Ministry of New and Renewable Energy, Ministry of Coal, and Ministry of Power) involved. Thus, given the wide scope, here we focus only on key programs that have direct links with the water, food, and environment sectors (Table 5).

The India's national solar mission aims to increase the share of solar energy in the total energy mix and different schemes [e.g., PM-KUSUM, Jawaharlal Nehru National Solar Mission (JNNSM)] have strong implications for the water and food sector. Recently launched Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (Prime minster farmers' energy security and upliftment initiative, PM-KUSUM) scheme aims to increase the use of solar energy for irrigation to meet agricultural needs and enhance farmers' income through installing solar power plants, incentivize farmers to use off-grid solar pumps and "solarize" grid-connected pumps.

Under component A, scheme aim to set up 10,000 MW of Decentralized Grid Connected Renewable Energy Power Plants, each with a capacity of 500 kW to 2 MW, by individual farmers/groups of farmers/cooperatives/panchayats/Farmer Producer Organizations (FPO)/Water User associations (WUA) on barren/fallow land. This can also be installed on cultivable land on stilts where crops can also be grown below the solar panels. Under component B, the scheme aims to the installation of 1.75 million stand-alone solar agriculture pumps of capacity up to 7.5 HP (financial support up to 7.5 HP only) for replacement of existing diesel Agriculture pumps/irrigation systems in off-grid areas, where grid supply is not available. Under component C, the scheme aims for the solarization of 1 million grid-connected agriculture Pumps. With grid-connected solar pumps, farmers will use the generated solar power to meet irrigation needs and can also sell the excess solar power to distribution companies at a pre-fixed tariff.

The scheme will have important nexus implications. First, it will contribute toward India's energy policy target of increasing renewable installed capacity and decreasing emissions from the agriculture sector. By replacing diesel pumps with off-grid solar, the demand for diesel fuel will be reduced which will reduce the demand for imported crude oil. At the same time, farmers will have an affordable source of irrigation, diesel being expensive, thus supporting increasing irrigation access and intensity. This will help increase production, and farmers' income but may aggravate pressure on the water. On-grid solar will help energy utilities reduce their subsidy burden as the power to agriculture is highly subsidized. Providing the farmers an opportunity to sell surplus energy will give them additional income and may reduce the perils of unsustainable groundwater abstraction associated with the availability of free or highly subsidized power.

In addition to solar, another focus is increasing the efficiency of energy use in agriculture under the National Energy Efficient Agriculture Pumps Programme and Agriculture Demand Side Management (AgDSM) Programme. The programme aims to replace farmers' inefficient pumps with Bureau of Energy Efficiency (BEE) star-rated pumps. With $\sim$ 20 million irrigation pumps in India, improving the efficiency of pumps (which is currently very low) have significant positive implication for the energy sector. Yet another energy scheme/goal that has strong implication for the WEFE sector is India's target of achieving 20% blending of biofuels (NITI Aayog, 2021) and developing new hydropower plants.

Hydropower is said to be the forgotten giant of clean electricity and has the potential to significantly contribute to meeting the net-zero emission goals of India. However, this would be feasible only if the country vigorously takes up development of unutilized hydro-potential. According to the Central Electricity Authority (CEA, 2022), the hydro-electric capacity yet to be developed (as of 2022) was 69% of the identified capacity of 1,48,701 MW. However, this needs to be pursued with timely and critical scientific appraisal for eco-friendly use of natural resources and minimizing societal impacts. The largest undeveloped potential to the tune of 54,329.0 MW is in the north eastern region, followed by 27,723.2 MW in the northern region. Over the past 5–6 decades, the share of hydropower to the total electricity generation has fallen progressively mainly because no significant addition could be made to the generation capacity. Presently, the share of private players in hydropower generation is very low, about 10%.

5.2.4. Programs in the ecosystem sector

Similar to the energy sector, the ecosystem sector is broad and very important. It covers a range of topics including wildlife, forestry, and ecology to which water, food, and energy securities are inextricably linked. Here we focus only on key programs that have a direct link with the water, energy, and food sectors (Table 6).

One of the key missions is the National Mission for Green India (NMGI), one of the eight missions under the National Action Plan on Climate Change (NAPCC). The mission recognizes the critical role forest plays in ecological sustainability, biodiversity conservation, and food-, water-, and livelihood security. The mission aim is to protect, restore and enhance forest cover to enhance ecosystem services. The target is to increase the land area under forest cover from 23 to 33%. The increase in forest cover will have important NEXUS implications. In terms of land, expansion of forest area may have a trade-off with land being used for food production or other activities. Similarly, change in land use influence water flows which may different implications at the local and basin (downstream vs. upstream) scale.

Government of India has also commenced schemes and programs for conserving wildlife habitats and natural ecosystems (e.g., biospheres, lakes, wetlands). For example, integrated development of wildlife habitats provides support to protected areas, protection of wildlife outside protected areas, and saving endangered species. The WEFE nexus becomes apparent considering the adverse impact of natural resource use expansion by the water, food, and energy sector on the environment. This includes cutting trees, expanding economic activities on reserved areas and lack of water in streams and rivers. In this regard regulation under the Environment protection act 1986 on minimum e-flows has direct trade-offs with water use from the river (for irrigation, and energy production).

6. Discussion

The review and analysis of the WEFE sector policies in India shows that the different policies were formed at different times. While the sectoral policies and programs related to WEFE in India are forward-looking, each of these supports optimal management and conservation of the concerned resource(s). Interconnection among these sectors and their interdependencies were not considered or inadequately considered while the policies were being developed. After attaining independence in 1947, one of the priorities of the Government of India was to provide food security to the nation. Recognizing the role of irrigation in food security, a number of programs were launched in water and agriculture sectors, without much attention to their impacts on other sectors. It is also noted that at that time, the ecosystem and nexus concept were not developed or were in the nascent stage.

With $\sim$ 50% of cropped area being rainfed and food security a priority, agriculture policy and programmes [e.g., National Food security mission and Minimum support price (MSP)] focus on increasing/sustaining foodgrain production. Initially, agricultural electricity tariffs in India were kept low so as to not burden poor farmers but the policy to provide free/subsidized power has continued. The outcome is unwise cropping pattern and uncontrolled use of ground water, leading to perverse WEF nexus with electricity utilities burdened by power subsidies. Besides significant negative impact on water and energy sector, these programs have promoted rice-wheat-sugarcane cropping cycles in many water stressed regions of India, leading to harmful impacts. Now, groundwater pumping is no longer driven by agricultural demand alone, it is rather dependent on the availability of cheap electricity. Shah and Vijayshankar (2022) pointed out that three "water guzzler" crops—rice, wheat, and sugarcane, have played a major role in water and food security. These crops occupy about 41% of the gross cropped area of India but consume more than 80% of irrigation water. Many times, these crops are being grown in places that are not suitable for them. They recommend that to break the perverse WEFE nexus, the best course correction is that the government should procure only those crops that match the agro-ecology of that region. Now many government policies and programmes are focusing on agro-ecology and natural farming. However, decision to change procurement policies will require strong political support.

Increasingly, there is recognition of Water and Food (and to an extent energy) nexus and the policies and programmes in these sectors are acknowledging the interdependence. For example, water sector policies and programs focus on improving irrigation efficiency (e.g., PMKSY) acknowledge agriculture as a major water user. Similarly, increasingly agriculture policies and programmes are focusing on crop diversification and low water use crops such millets and pulses. This is a positive development from the nexus angle. Another example of realizing WEFE nexus is the attention on solar energy based irrigation in India (e.g., PM-KUSUM scheme). Solar irrigation offers a sustainable solution by harnessing renewable energy to power irrigation systems, thereby reducing the reliance on electricity subsidies and diesel and mitigating greenhouse gas emissions (ecosystem synergy). Solar-powered irrigation systems provide farmers with access to water for crop cultivation, particularly in areas with limited grid connectivity or unreliable electricity supply thus expanding irrigation (water system synergy). However, there are also concerns that in the absence of regulation, these systems may increase groundwater withdrawal, harming sustainability.

In any case, the synergies need to be further strengthened. Recent studies have shown a weakening trend of the Indian summer monsoon (ISM) attributed to the warming of the western Indian Ocean, high emission of aerosol in northern India and large-scale land use land cover change (see, for example, Sagar et al., 2023). Studies suggest that the number of droughts and their severity will increase in the future. Increased groundwater pumping results in falling water tables and hence, subsequently more energy would be required to pump water. Increased cost of irrigation affects the crop prices and that, in turn, makes food unaffordable to the marginal population. This has resulted in a vicious circle where, to maintain the food security, groundwater and energy are overexploited, leading to further declines. Rasul and Sharma (2016) opined that the nexus approach additionally provides a path to adapt to the impacts of climate change.

Review of the programs also brings out the need of intra- and inter-sectoral convergence as there are overlaps in some programs. Some of these overlaps will lead to a waste of effort and resources and it is desirable to remove them. To assess this and make policy decisions, there will need to quantify these trade-offs and synergies. Multiple studies have applied diverse methodologies including footprint accounting framework, system dynamic model and water economic models to quantify the WEF nexus (Chang et al., 2016; Bakhshianlamouki et al., 2020; Lee et al., 2020; Zhang et al., 2022). For example, Lee et al. (2020) developed a tool called the WEF Nexus Phosphate (WEF-P) Tool to evaluate the impact of phosphate industry on WEF sectors in a mining region of Morocco. This tool is a decision support system to carry quantifiable trade-off analyses for management decisions including water allocation. It can help quantify the products (phosphate) and water and energy footprints across the supply chain, identifies the interlinkages between water and energy in phosphate production and transport, and establishes reference values for comparison of outcomes and performance. Thus, the WEF-P allows the user to evaluate trade-offs between water resource allocations and the impact of the Moroccan phosphate industry with agricultural water use. Similar tools and approaches could be used to quantify trade-offs and synergies across India government policies and programs.

Hoekstra and Mekonnen (2012) quantified water footprint of humanity at a high spatial resolution. They estimated water footprints for nations from both a production and consumption perspective. Agricultural production accounts for the largest share (92%) in water footprints. Based on the estimations of international virtual water flows, their study quantified the global patterns of water consumption and pollution and showed that several countries heavily depend on and are using water resources of the other countries. Transfer of large quantity of water through international virtual water flows shows that water and food security of a nation also depends on how much water and food that country is importing or exporting through virtual route.

6.1. WEFE nexus and sustainable development goals

Sustainable Development Goals (SDGs) were adopted by the General Assembly of United Nations Member States in 2015 as a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. The 17 SDGs (United Nations, 2015) have been built on the principle of "leaving no one behind" which means that true development would be realized only when the needs of the people at the bottommost ladder are addressed. With this view, Agenda 2030 emphasizes a holistic approach to achieving sustainable development for all. SDGs are integrated which means that goal achievements will affect attainments in other goals. Figure 3 shows the 17 SDGs.

All the SDGs are of relevance to the WEFE sectors but the Goal 2 (zero hunger), Goal 3 (good health and wellbeing), Goal 6 (clean water and sanitation), Goal 7 (affordable and clean energy), and Goal 13 (climate action) are directly concerned with WEFE sectors. Other SDGs that are significantly relevant to WEFE sectors are Goal 1: No Poverty; Goal 11: Sustainable Cities and Communities, Goal 12: Responsible Consumption and Production, Goal 14: Life Below Water, and Goal 15: Life on Land.

Some recent publications have examined the SDGs from a nexus lens. For example, Liu et al. (2018) proposed a procedure to implement nexus approaches. The website https://www.un.org/ presents a graphical description, "A Nexus Approach For The SDGs", highlighting interlinkages between various SDGs.

6.2. Key challenges and barriers to WEFE nexus implementation

As mentioned earlier, despite the obvious advantages, the nexus concept has found limited applications in real life. Ever since the nexus concept gained prominence, many attempts have been made to address the knowledge gaps and weaknesses with the concept. Abdi et al. (2020) and Purwanto et al. (2021) reviewed research related to WEF knowledge gaps, criticisms, and areas for improvement. Among identified gaps, a vague definition of the nexus concept can be a barrier to applications and a restrictive definition could hamper development. Further, multiple methodologies have been used in nexus studies whose relative merits/demerits are not known. To fill this gap, Anandhi et al. (2022) provided a framework for developing definitions and conceptualization toward implementing WEFE nexus projects. The suggested framework was developed based on detail review of existing studies and synthesis of current knowledge.

Many regions face lack of data to implement the nexus approach. For example, acquiring comprehensive and timely data on water, energy, food, and environment data in regions with limited resources is a challenge. This becomes critical since the WEFE approach requires integrated data sets which is hindered due to lack or disparities in quality and consistency in data across sectors and regions. Addressing data limitations is vital for realizing the potential benefits of the WEFE nexus.

Implementation of the WEFE nexus approach is also hindered by a number of governance challenges including weak institutions, lack of cross-sectoral coordination and collaboration among various government bodies and stakeholders. Due to sectoral and siloed approach, there is lack of communication across sectors but also between engineers/scientists, policy-makers, and the public which all translates to limited implementation of the nexus concept in policy development. There are no existing national or international policy frameworks that explicitly address coordination of WEF nexus (Pahl-Wostl, 2019). For example, Pardoe et al. (2018) studied the WEF nexus in Tanzania and reported that though agriculture and water sectors are increasingly integrating climate change into

FIGURE 3
The 17 SDGs. Source: https://sdgs.un.org/goals.

policies and plans, the practical coordination on adaptation is relatively superficial. Publication of the national adaptation action plan marked a step change in integrating climate change into sectoral policies and plans but appeared to have led to a sectoral approach to managing impacts of climate change. Inter-sectoral action suffered due to institutional constraints, restricting opportunities for collaboration. This requires institutional frameworks that can address these constraints.

Published literature mentions two weaknesses in the WEF nexus: the livelihoods and the environment are often omitted (Simpson and Jewitt, 2019). The second aspect is considered in many nexus studies but the first one is still a concern. Further, the nexus studies have largely focused on macro-scale resource security with little guidance to local-scale decision making. Effective implementation of WEFE nexus requires governance and institutional frameworks that can address these constraints. This is a challenge in several regions where governance structures and capacity is limited. Also balancing the interest of different sectors and stakeholders is a challenging task (Pahl-Wostl, 2019). It's difficult for different parts of the government to cooperate because they have strict rules, powerful interests, and established communication systems in their own areas. For example, imbalance in power among sectors (e.g., primacy of agriculture over water or water over environment) and lobbying from sector is a further barrier (Pahl-Wostl, 2019).

In an effort to assess convergence in perspectives regarding WEF challenges, estimate the levels of communication among the researchers, regional stakeholders and the WEF organizations, barriers and opportunities to improve communication among all categories of stakeholders, Daher et al. (2020) carried out a survey-based study in San Antonio Region, Texas (USA) which is a hotspot, witnessing rapid urbanization, growing energy, and agricultural production. The study found that the levels of communication among the groups were modest and on many topics, all the stakeholders had similar views. Improvement in communication and sharing of information was identified as a pre-requisite to improve cooperation and better address the challenges in management of interconnected resource. The methodology provides a framework to assess agreement on WEF strategies and understating in other regions.

The governance issues are also accentuated by lack of awareness and understanding of the nexus principle and experience poses additional constraints. To start with, many WEFE sector professionals are not fully aware of the concept and its advantages. Some practitioners and researchers also tend to compare the nexus approach with Integrated Water Resource Management (IWRM) and do not have a clear view of the comparative merits of the two. The main difference between Nexus and IWRM is that IWRM is water focused and looks at the problem from water lens. The WEFE Nexus approach looks at all the four elements as part of interrelated system where the interrelationships are explicitly considered.

In most countries, people have limited implementation of the nexus principle and experience. Lack of communication between engineers/scientists, policy-makers, and the public is also a reason for limited implementation of the nexus concept in policy development. Senior-level decision-makers are to be sensitized on the advantages of the nexus approach in policy formulation. Besides, more efforts are required from the researchers regarding the conversion of results of the nexus studies to action points. Outcomes of nexus studies would be of practical help when there is a long-term stable vision in policy and plans.

A challenge for WEFE nexus analyses also stems from globalization. Liberalization of trade has meant that the interactions between water, energy, and food are more complex since materials and products are continually crossing international borders (Owen et al., 2018). Water moves between countries as "virtual water" through food and other products. Due to this movement, the domain in a nexus study becomes difficult to define. Further, the nexus studies have largely focused on macro-scale resource security with little guidance to local-scale decision making. This is highlighted by Purwanto et al. (2021) which highlighted that the local viewpoints are often under-represented, especially in developing countries with centralized governances. Thus, context-specific, practical and policy implementation guidance in evaluation and planning still needs to be improved. For holistic and equitable resource management, locally based WEFE management will help. There is also a dearth of successful case-studies. For the nexus approach to succeed, stakeholder participation needs to be insured. Some suggestions of Purwanto et al. (2021) that are relevant to India include reliable and valid data, nexus that is adaptable to diverse situations and is applicable across a range of scales.

Many initiatives would be required to take the nexus approach forward. Nexus communities and networks would have to be set up along with online platforms to assimilate knowledge and data. The knowledge created needs to be shared widely. A possible way could be through annual meetings/conferences where experts and practitioners come together to share knowledge and experiences. Websites/portals can be developed to communicate outcomes, and success stories. For the growth of nexus knowledge, it will help if funds are raised, mechanisms are established to invite research proposals, review them, fund the studies, and for monitoring progress. Studies also conclude (for example, Grey and Sadoff, 2007) that providing WEFE security is becoming progressively tougher for the countries that lack such security. Particularly, most water-insecure countries face much greater challenges than those faced by the countries that could achieve water security in the last century.

7. Conclusions

Without following a water-energy-food-ecosystem nexus approach, unintended consequences may arise with actions in one sector having negative externalities on the other inter-linked sectors. The review of policies and programs related to water, energy and food sectors in India presented in the paper shows that consideration of interconnectedness among these sectors and their interdependencies in a nexus thinking has apparently received less attention. Some sectoral programmes need to be modified to address livelihood and local-scale resource management. Fast changing development scenarios in these sectors and looming climate change demand that nexus concepts be adopted better address synergies and manage trade-offs. It is time that the relevant policies and programs are reviewed and made nexus compliant. Besides developing coherent policies and programs in the WEFE sectors, concerted efforts are needed for developing nexus specific analytical framework and tools/methods including integrated modeling assessments in a systems approach for informed policy development.

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.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frwa.2023.1128198/full#supplementary-material

References

Abdi, H., Shahbazitabar, M., and Mohammadi-Ivatloo, B. (2020). Food, energy and water nexus: a brief review of definitions, research, and challenges. *Inventions* 5, 56. doi: 10.3390/inventions5040056

Alam, M. F., McClain, M., Sikka, A., and Pande, S. (2022). Understanding human–water feedbacks of interventions in agricultural systems with agent based models: a review. *Environ. Res. Lett.* 17, 103003. doi: 10.1088/1748-9326/ac91e1

Albrecht, T. R., Crootof, A., and Scott, C. A. (2018). The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environ. Res. Lett.* 13, 043002. doi: 10.1088/1748-9326/aaa9c6

Anandhi, A., Srivastava, P., Mohtar, R. H., Lawford, R. G., Sen, S., and Lamba, J. (2022). Methodologies and principles for developing nexus definitions and conceptualizations. *J. ASABE.* 66, 205–230. doi: 10.13031/ja.14539

Bach, H., Bird, J., Clausen, T. J., Jensen, K. M., Lange, R. B., Taylor, R., et al. (2012). *Transboundary river basin management: Addressing water, energy and food security.* Lao PDR: Mekong River Commission.

Bakhshianlamouki, E., Masia, S., Karimi, P., van der Zaag, P., and Sušnik, J. (2020). A system dynamics model to quantify the impacts of restoration measures on the water-energy-food nexus in the Urmia lake Basin, Iran. *Sci. Total Environ.* 708, 134874. doi: 10.1016/j.scitotenv.2019.134874

Bali, N., Sidhartha, V., and Vaishali, M. (2020). *Electricity Access and Benchmarking of distribution utilities in India.* New Delhi: Smart Power India-powered by The Rockefeller Foundation. Available online at: https://www.niti.gov.in/sites/default/files/2020-11/SPI_Electrification_15.pdf (accessed December, 2022).

Barik, B., Ghosh, S., Sahana, A. S., Pathak, A., and Sekhar, M. (2017). Water–food–energy nexus with changing agricultural scenarios in India during recent decades. *Hydrol. Earth Syst. Sci.* 21, 30413060. doi: 10.5194/hess-21-3041-2017

Beddington, J., Asaduzzaman, M., Fernandez, A., Clark, M., Guillou, M., Jahn, M., et al. (2011). *Achieving food security in the face of climate change: Summary for policy makers from the Commission on Sustainable Agriculture and Climate Change.* Copenhagen, Denmark: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

Belinskij, A. (2015). Water-energy-food nexus within the framework of international water law. *Water* 7, 5396–5415. doi: 10.3390/w7105396

CEA. (2022). *All India Electricity Statistics - General Review 2022 (Containing Data for the Year 2020-21).* New Delhi: Central Electricity Authority, Govt. of India.

CFS. (2014). *Global Strategic Framework for Food Security and Nutrition (GSF).* Committee on World Food Security. Available online at: https://www.fao.org/fileadmin/templates/cfs/Docs1314/GSF/GSF_Version_3_EN.pdf (accessed December, 2022).

CGWB. (2022). "National compilation on dynamic ground water resources of India," in *2022. Faridabad, India: Ministry of Water Resources, River Development and Ganga Rejuvenation, Government of India* (Central Ground Water Board).

Chang, Y., Li, G., Yao, Y., Zhang, L., and Yu, C. (2016). Quantifying the water-energy-food nexus: current status and trends. *Energies* 9, 65. doi: 10.3390/en9020065

CPCB (2022). *Polluted river stretches for restoration of water quality.* Delhi: Central Pollution Control Board (CPCB); Ministry of Environment, Forests & Climate Change (MoEF & CC).

CSE (2021). *State of India's Environment 2021.* New Delhi: Centre for Science and Environment.

DAC&FW. (2004a). National Agriculture Policy 2000. Ministry of Agriculture and Farmers Welfare, Government of India. Available online at: https://pib.gov.in/newsite/erelcontent.aspx?relid=991 (accessed December, 2022).

DAC&FW. (2004b). *National Policy for Farmers 2007. Ministry of Agriculture and Farmers Welfare, Government of India.* Available online at: https://agricoop.nic.in/sites/default/files/npff2007%20%281%29.pdf (accessed December, 2022).

DAC&FW. (2019). National Mission for Sustainable Agriculture. Ministry of Agriculture and Farmers Welfare, Government of India. Available online at: https://nmsa.dac.gov.in/ (accessed December, 2022).

Daher, B., Hannibal, B., Mohtar, R. H., and Portney, K. (2020). Toward understanding the convergence of researcher and stakeholder perspectives related to water-energy-food (WEF) challenges: The case of San Antonio, Texas. *Environ. Sci. Policy.* 104, 20–35. doi: 10.1016/j.envsci.2019.10.020

de Amorima, W. S., Valdugab, I. B., Pereira Ribeiroa, J. M., Williamsonc, V. G., Krauserd, G. E., and Magtotoe, M. K. (2018). The nexus between water, energy, and food in the context of the global risks: An analysis of the interactions between food, water, and energy security. *Environ. Impact Assess. Rev.* 72, 1–11. doi: 10.1016/j.eiar.2018.05.002

Department of Drinking Water and Sanitation (2023). *Jal Jeevan Mission - Har Ghar Jal Dashboard.* Department of Drinking Water and Sanitation, Ministry of Jal Shakti, Government of India. Available online at: https://ejalshakti.gov.in/jjmreport/JJMIndia.aspx (accessed August 22, 2023).

DoA&C. (2014). *National Agroforestry Policy 2014.* New Delhi: Department of Agriculture and Cooperation Ministry of Agriculture, Government of India. Available online at: https://agricoop.nic.in/sites/default/files/National%20Agroforestry%20Policy%202014.pdf (accessed December, 2022).

DoA&FW. (2022). *Annual report 2021-22. Department of Agriculture and Farmers Welfare Ministry of Agriculture and Farmers Welfare Government of India.* New Delhi.

DoF&PD. (2022). National Food Security Act, (NFSA) 2013. Department of Food and Public distribution. Available online at: https://nfsa.gov.in/portal/nfsa-act (accessed December, 2022).

Endo, A., Burnett, K., Orencio, P. M., Kumazawa, T., Wada, C. A., Ishii, A., et al. (2015). Methods of the water-energy-food nexus. *Water* 7, 58065830. doi: 10.3390/w7105806

FAO, IFAD, UNICEF, WFP, and WHO. (2018). *The state of food security and nutrition in the world 2018. Building climate resilience for food security and nutrition.* Rome. Available online at: http://www.fao.org/3/I9553EN/i9553en.pdf

FAO. (2014). *The Water-Energy-Food Nexus A new approach in support of food security and sustainable agriculture*. Rome: Food and Agriculture Organization of the United Nations.

FAO. (2023). *India at a glance. Food and Agriculture Organisation of the United Nations.* Available online at: https://www.fao.org/india/fao-in-india/india-at-a-glance/en/ (accessed December, 2022).

Government of India. (2022). *India's Updated First Nationally. Determined Contribution Under Paris Agreement (2021-2030): August 2022 Submission to UNFCCC.* Available online at: https://unfccc.int/sites/default/files/NDC/2022-08/India%20Updated%20First%20Nationally%20Determined%20Contrib.pdf (accessed December, 2022).

Grey, D., and Sadoff, C. W. (2007). Sink or Swim? Water security for growth and development. *Water Policy* 9, 545–571. doi: 10.2166/wp.2007.021

Hoekstra, A. Y., and Mekonnen, M. M. (2012). The water footprint of humanity. *PNAS* 109, 3232–3237. doi: 10.1073/pnas.1109936109

Hoff, H. (2011). "Understanding the Nexus," in *2011 Conference: The Water, Energy and Food Security Nexus* (Stockholm: Stockholm Environment Institute).

IEA. (2022). Energy security. Available online at: https://www.iea.org/topics/energy-security (accessed December, 2022).

IPCC. (2019). Summary for Policymakers. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems.

Jain, S. K., Agarwal, P. K., and Singh, V. P. (2007). *Hydrology and Water Resources of India*. Dordrecht: Springer.

Jain, S. K., and Kumar, P. (2014). Environmental flows in India: towards sustainable water management. *Hydrol. Sci. J.* 59, 751–769. doi: 10.1080/02626667.2014.896996

Kholod, N., Evans, M., Khan, Z., Hejazi, M., and Chaturvedi, V. (2021). Water-energy-food nexus in India: A critical review. *Energy Clim. Change* 2, 100060. doi: 10.1016/j.egycc.2021.100060

Lee, S. H., Assi, A. T., Daher, B., Mengoub, F. E., and Mohtar, R. H. (2020). A Water-Energy-Food Nexus approach for conducting trade-off analysis: Morocco's phosphate industry in the Khouribga region. *Hydrol. Earth Syst. Sci.* 24, 4727–4741. doi: 10.5194/hess-24-4727-2020

Leese, M., and Meisch, S. (2015). Securitising sustainability? Questioning the "Water, Energy and Food-Security Nexus". *Water Alternat.* 8, 695–709. Available online at: https://www.water-alternatives.org/index.php/alldoc/articles/vol8/v8issue1/272-a8-1-5

Liu, J., Hull, V., Godfray, H. C. J., Tilman, D., Gleick, P., Hoff, H., et al. (2018). Nexus approaches to global sustainable development. *Nat. Sustain.* 1, 466–476. doi: 10.1038/s41893-018-0135-8

Ministry of Power. (2022). *Annual report 2021-22. Ministry of Power, Government of India*. New Delhi. Available online at: https://powermin.gov.in/sites/default/files/uploads/MOP_Annual_Report_Eng_2021-22.pdf (accessed December, 2022).

MoE&F. (1988). *National Forest policy 1988. Ministry of Environment and Forests, Government of India, New Delhi.* Available online at: https://asbb.gov.in/Downloads/National%20Forest%20Policy.pdf (accessed December, 2022).

MoEF&CC. (2022). *EIA Notification, 2006 and subsequent amendments*. New Delhi: Ministry of Environment and Forests, Government of India. Available online at: http://environmentclearance.nic.in/report/EIA_Notifications.aspx (accessed December, 2022).

MoWR. (2012). *National Water Policy. Ministry of Water Resources, Government of India.* Available online at: http://jalshakti-dowr.gov.in/sites/default/files/NWP2012Eng6495132651_1.pdf (accessed December, 2022).

Müller, F., Jones, K. B., Krauze, K., Li, B., Victorov, S., Petrosillo, S., et al. (2008). "Contributions of Landscape Sciences to the Development of Environmental Security, In Use of Landscape Sciences for the Assessment of Environmental Security," in *NATO Science for Peace and Security Series C: Environmental Security* (Dordrecht: Springer).

Naidoo, D., Nhamo, L., Mpandeli, S., Sobratee, N., Senzanje, A., Liphadzi, S., et al. (2021). Operationalising the water-energy-food nexus through the theory of change. *Renew. Sustain. Energy Rev.* 149, 111416. doi: 10.1016/j.rser.2021.111416

National Biodiversity Authority. (2004). *The Biological Diversity Act, 2002 and Biological Diversity Rules, 2004.* Chennai. Available online at: http://nbaindia.org/uploaded/act/BDACT_ENG.pdf (accessed December, 2022).

NITI Aayog. (2017). *Draft National Energy Policy NITI Aayog, Government of India.* Available online at: https://smartnet.niua.org/sites/default/files/resources/NEP-ID_27.06.2017.pdf (accessed December, 2022).

NITI Aayog. (2021). *Roadmap for Ethanol Blending in India 2020-25. Government of India.* Available online at: https://www.niti.gov.in/sites/default/files/2021-06/EthanolBlendingInIndia_compressed.pdf (accessed December, 2022).

Owen, A., Scott, K., and Barrett, J. (2018). Identifying critical supply chains and final products: an input-output approach to exploring the energy-water-food nexus. *Appl. Energy* 210, 632642. doi: 10.1016/j.apenergy.2017.09.069

Pahl-Wostl, C. (2019). Governance of the water-energy-food security nexus: A multi-level coordination challenge. *Environ. Sci. Policy* 92, 356–367. doi: 10.1016/j.envsci.2017.07.017

Pahl-Wostl, C., Gorris, P., Jager, N.,·Koch, L., Lebel, L., Stein, C., et al. (2021). Scale-related governance challenges in the water–energy–food nexus: toward a diagnostic approach. *Sustain. Sci.* 16, 615–629. doi: 10.1007/s11625-020-00888-6

Pardoe, J., Conway, D., Namaganda, E., Vincent, K., Dougill, A. J., and Kashaigili, J. J. (2018). Climate change and the water–energy–food nexus: insights from policy and practice in Tanzania. *Clim. Policy* 18, 863–877. doi: 10.1080/14693062.2017.1386082

Purwanto, A., Sušnik, J., Suryadi, F. X., and de Fraiture, C. (2021). Water-energy-food nexus: critical review, practical applications, and prospects for future research. *Sustainability* 13, 1919. doi: 10.3390/su13041919

Rakitskaya, K. (2021). *Water energy food nexus in India: a review of interlinkages and challenges for a sustainable development*. Master thesis in Sustainable Development. Department of Earth Sciences, Uppsala University, Sweden.

Rasul, G., and Sharma, B. (2016). The nexus approach to water–energy–food security: an option for adaptation to climate change. *Clim. Pol.* 16, 682–702. doi: 10.1080/14693062.2015.1029865

Ratner, B. D. (2018). *Environmental Security: Dimensions and Priorities.* Washington, DC: Scientific and Technical Advisory Panel to the Global Environment Facility.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin III, F. S., Lambin, E. F., et al. (2009). A safe operating space for humanity. *Nature* 461, 472–475. doi: 10.1038/461472a

Rodell, M., Velicogna, I., and Famiglietti, J. S. (2009). Satellite-based estimates of groundwater depletion in India. *Nature* 460, 999–1003. doi: 10.1038/nature08238

Sagar, A., Krishnan, R., and Sabin, T. P. (2023). Anthropogenically-forced weakening of the Indian summer monsoon and enhancement of the western North Pacific tropical cyclogenesis. *Front. Earth Sci. Sec. Atmosph. Sci.* 11, 1149344. doi: 10.3389/feart.2023.1149344

Sarkodie, S. A., and Owusu, P. A. (2020). Bibliometric analysis of water–energy–food nexus: Sustainability assessment of renewable energy. *Curr. Opin. Environ. Sci. Health* 13, 29–34. doi: 10.1016/j.coesh.2019.10.008

Shah, M., and Vijayshankar, P. S. (2022). "Symbiosis of Water and Agricultural Transformation in India," in *Chapter in Indian Agriculture Towards 2030*, *India Studies in Business and Economics,* eds. R., Chand, P., Joshi, and S., Khadka (Rome: Food and Agriculture Organization of the United Nations). doi: 10.1007/978-981-19-0763-0_5

Sikka, A. K., Alam, M. F., and Pavelic, P. (2020). Managing groundwater for building resilience for sustainable agriculture in South Asia. *Irrig. Drain.* 14, 2558. doi: 10.1002/ird.2558

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

Spang, E. S., Moomaw, W. R., Gallagher, K. S., Kirshen, P. H., and Marks, D. H. (2014). The water consumption of energy production: an international comparison. *Ecosyst. Res. Lett.* 9, 105002. doi: 10.1088/1748-9326/9/10/105002

The Economist. (2022). *The Global Food Security Index 2022.* Available online at: https://impact.economist.com/sustainability/project/food-security-index (accessed December, 2022).

UN Water. (2013). *What is Water Security?* Available online at: https://www.unwater.org/publications/what-water-security-infographic (accessed December, 2022).

UNDP. (1994). *Human Development Report 1994: New Dimensions of Human Security*. New York: United Nations Development Programme.

UNECE. (2022). *Water-food-energy-ecosystem nexus. United Nations Economic Commission for Europe (UNECE).* Available online at: https://unece.org/environment-policy/water/areas-work-convention/water-food-energy-ecosystem-nexus#:~:text=The%20%E2%80%9Cnexus%E2%80%9D%20term%20in%20the,human%20activities%20ultimately%20depend%20upon (accessed December, 2022).

UNESCAP (2013). *The status of the water-food-energy nexus in Asia and the Pacific*. United Nations Publication.

United Nations. (1992). *Convention on Biological Diversity.* Available online at: https://www.cbd.int/doc/legal/cbd-en.pdf (accessed December, 2022).

United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development.* Available online at: https://documents-dds-ny.un.org/doc/UNDOC/GEN/N15/291/89/PDF/N1529189.pdf?OpenElement (accessed December, 2022).

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., et al. (2010). Global threats to human water security and river biodiversity. *Nature* 467, 555–561. doi: 10.1038/nature09440

WEF. (2011). "An integrated sustainability index for effective water policy," in *Water security: the water-food-energy-climate nexus. World Economic Forum, Water Initiative,* ed. D., Waughray (Washington, Covelo, London: Island Press) 271.

WMO (2022). *2022 State of Climate Services - Energy.* Geneva: World Meteorological Organisation (WMO). Available online at: https://public.wmo.int/en/our-mandate/climate/state-of-climate-services-report?fbclid=IwAR2In-Tord3BTl5PBIgBAav7ncg2UkfLw8K4Zny3J8tzItBnYywX8Qap4uU

World Summit on Food Security. (2009). *Draft Declaration of the World Summit on Food Security.* Rome: Food and Agriculture Organization of the United Nations. Available online at: http://www.fao.org/fileadmin/templates/wsfs/Summit/Docs/Declaration/WSFS09_Draft_Declaration.pdf (accessed December, 2022).

Zhang, P., Cai, Y., Zhou, Y., Tan, Q., Li, B., Li, B., et al. (2022). Quantifying the water-energy-food nexus in Guangdong, Hong Kong, and Macao regions. *Sustain. Prod. Consumpt.* 29, 188–200. doi: 10.1016/j.spc.2021.09.022

Zurlini, G., and Muller, F. (2008). "Environmental security," in *Encyclopedia of Ecology,* eds. S. E., Jørgensen, and B. D., Fath (Oxford: Elsevier) 1350–1356. doi: 10.1016/B978-008045405-4.00707-2