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Role of water-energy-food nexus in environmental management and climate action

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ABSTRACT

The demand for water, energy, and food resources increased in tandem with the world's population, industrialization, and urbanization. Anthropogenic sources of environmental pollutants degrade the water resources while population expansion contributes to rising demand for non-renewable energy resources which further enhances the greenhouse gas emissions. Also, maintaining the food security/-safety is another challenge which needs to be addressed for securing 'planetary public health'. The sustainability programs, pragmatic studies, and strategies from regulatory/scientific institutions attempt to reduce the depletion of these resources and mitigate environmental challenges however, the individualistic approaches proves to be inadequate. Therefore, the present review emphasizes the use of Water-Energy-Food (WEF) Nexus as a tool to combat environmental degradation, address climate action, and achieve the Sustainable Development Goals (SDGs). In this article, we investigate methodological paradigm and application of WEF Nexus in an inter-related framework through case studies on water resources, energy efficiency, urban food production, food waste reduction, cross-sectoral perspectives, and the circular economy. It has been widely observed that excessive exploitation of these resources influences the global food supply and demand, water availability, resilience in energy and socio-economic sector. Also, such perturbations in water, energy, and food sectors were found to be inextricably linked with climate change. The results further revealed that WEF nexus approach stimulates multilevel and inter-sectoral governance, thereby aiding to address the complexities and inefficiencies in achieving the SDGs. The prioritization of WEF Nexus strategy, especially under the event of COVID-19 can be a holistic approach to sustainably utilise natural resources to help achieve the environmental sustainability.

1. Introduction

Environmental degradation driven by multiple anthropogenic perturbations adversely influenced the multiple environmental matrices such as water and soil, especially those of agriculture systems [1]. This necessitated the need to conserve the quantity and quality of water resources along-with maintaining the food security/-safety [1,2]. Further, the abrupt surge in demand for natural resources (e.g., water, energy, food, gases, and fossil fuels) are driven by population growth, industrialization, urbanization, modern intensive agriculture, changing lifestyles, cultural and technological change which resulted in the depletion of non-renewable sources [2]. Also, these factors escalated the energy demand of non-renewable sources which is tightly linked with greenhouse gaseous (GHGs) emissions [1]. The challenges related with environmental sustainability and energy resilience are further exacerbated due to altered interactions amongst various socio-ecological, socio-political, and socio-economy sectors in COVID-19 pandemic [3–6]. Therefore, concerted efforts to address issues related with environmental sustainability, natural resource degradation, and energy security is need of the hour.

Lack of sufficient water resources at global scale adversely influenced the human well-being and can further be an impediment to address other existing challenges such as poverty, economic growth, environmental degradation, desertification, climate change, and food security [9,10]. In addition to water, achieving energy resilience in various manufacturing and production sectors is a major challenge to meet environmental sustainability [7]. Energy resilience is also necessary to balance economic expansion with-in environmental limits and carrying capacity of ecosystems to maintain nature sustainability [8]. Also, maintaining food security is a global challenge and a serious concern in many developing countries [9]. The rise in global population has escalated the demand for food stuffs that stressed the land-use

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assigned to agriculture, water resources, and sufficient energy to create sustainable food systems [2]. The world energy system can be improved immensely by accelerating the transition to sustainable and renewable energy systems, however, so far the progress seems to be inadequate [10]. Nevertheless, sustained efforts along-with financial incentives are required in attaining the energy resilience to sufficiently address the current climatic concerns and carbon neutral future [11]. The Intergovernmental Panel on Climate Change also advocated the systematic efforts for attaining energy resilience so that by 2050, renewable energy sources may be able to provide between 70% and 85% of the world's electricity [12]. Despite the high electricity demand, developing countries are anticipated to play a significant role in the energy transition since they now possess the majority of the available renewable energy potential [13].

Past studies attempted to address the challenges linked with the water, energy, and food sectors [14–17]. However, a holistic approach integrating the utility of WEF Nexus in environmental management and climate action was lacking. The individualistic approach in addressing the WEF related issues left the other interrelated problem unaddressed. Interestingly, as mitigation measures of one environmental challenge advances, there may be trade-offs or synergies with issues linked with another sectors [18,19]. Therefore, it has now increasingly being realised that the challenges linked with water resources, energy resilience, and food security are interconnected and cannot be managed separately [20]. Moreover, the existing sectoral approaches to address environmental challenges can also undermine the efforts towards mitigating climate change and often create imbalances which impede the progress of sustainable development programs [21]. Since the climate change impacts are considered to be multi-dimensional, therefore there exists an urgent need of the cross-sectoral perspective to adequately respond to this global challenge. Therefore, climate action can be addressed effectively with incorporation of WEF Nexus approaches [22].

A cross-sectoral approach is therefore the need of the hour to address climate action and sustainable environmental management [23]. Since water, energy, and food resources are inextricably linked with the on-going climate change, therefore, the issues linked with these resources can be addressed sufficiently through incorporation of WEF Nexus framework in proposed mitigation measures [23]. The need of WEF Nexus is further ascertained at global scale as about 844 million people do not have access to safe drinking water [24]. Further 1.1 billion people do not have access to clean energy and incidentally 50% of them belongs to African continent [25]. In this respect, around 815 million people also do not have secure access to food in order to fulfil their dietary and nutritional requirements [26]. To this end, the WEF nexus offers the integrated approach to analyse the synergies and trade-offs amongst the water, energy, and food sectors in order to manage and maximise the sustainable utilisation of these resources [2].

In recent decade, few studies therefore, investigated the solutions of environmental problems in WEF Nexus framework [27–30]. Few reviews have been made on how the nexus approach provides a practical perspective in relation to environmental sustainability [31]. Other discussions tried to explore that how the nexus approach can be effectively implemented for climate change adaptation [32]. However, knowledge gaps still exist in adequate exploration of cross-sectoral application of WEF Nexus to achieve human well-being, energy resilience, food security, and sustainable environment. Hence, this review attempts to provide a link between the WEF Nexus and the SDGs as an integrated tool for climate change mitigation.

The incorporation of WEF Nexus in environmental management can also facilitate the United Nations (UN) SDGs. The UN has presented 17 SDGs to address climate change along-with other environmental and socio-economic problems to help achieve sustainable development [33]. The UN resolutions on SDGs and approved objectives are intimately linked with the sustenance of water, energy, and food resources [34]. Nevertheless, prior to the pandemic, there has been uneven progress toward achieving the17 SDGs, which was further hampered after the outbreak of COVID-19 [35]. To this end, the water, energy, and food (WEF) Nexus strategy is also an effective tool for attaining the SDGs by 2030 [33,36].

The studies conducted on WEF Nexus after 2016 did not assess the effects of COVID-19 on its functional aspects and implementation. The COVID-19 pandemic has been especially devastating to developing nations especially in terms of adequate availability and distribution of water and food resources [37]. The pandemic restrictions on mobility have led to shortages of agricultural output, enforcing farmer livelihood losses, and resulting in an inadequate food supply [38]. The pandemic has also caused fluctuations in energy demand and pattern of consumption [39]. Also, the COVID-19 outbreak resulted in an increased use of water resources, especially in domestic and healthcare sectors [39]. Furthermore, majority of SDGs especially SDG 2 (Zero Hunger), 6 (Clean water and sanitation) and 7 (Affordable and clean energy) are projected to suffer setbacks due to the adverse impacts of COVID-19 which further jeopardize efforts towards attaining SDG 13 i.e., climate action [40,34].

In light of the above knowledge gaps the present article attempts to provide state of art information on the "WEF Nexus", its functionality, and its relevance for environmental remediation and climate change mitigation. Present discussion also attempted to investigate the relevance of managing the multiple nexus sectors to promote synergies and to monitor and reduce trade-offs by using the interactions amongst multiple sectors. Additionally, the interactions amongst the various sectors of the WEF Nexus were also investigated in this review. Further, the discussion extends to investigate that how interactions amongst three sectors (i.e., water, energy, and food) can be the strong driving force behind accelerating the efforts towards environmental management and climate action. The potential use of WEF Nexus approach in the achieving the resilience in energy and economic sectors as well as augmentation of the progress towards attaining SDGs was further investigated. The impact of COVID-19 on the multiple sectors of the WEF Nexus and achievement of the SDGs were also investigated. The linkage between the WEF sectors and SDGs were also investigated so as to attain energy resilience, food and water security, to promote environmental sustainability and circular economy. In brief, this review paper aims to emphasize the use of Water-Energy-Food (WEF) Nexus as a tool to address climate action and environmental management which can effectively accelerate the achievement of SDGs.

2. Methodology

The methodology used in this article consists of a thorough analysis of academic literature and the proposition of a systematic implementation of the nexus concept. 'Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)' was used in the identification and selection of articles in the methodology [41]. In this respect, Fig. 1(a) explicitly elucidates the schematic lay-out of the PRISMA and different steps elaborating the role of WEF Nexus indicators in environmental management, energy resilience, and climate action. Step 1 presents the research platforms used i.e., ScienceDirect and Google Scholar. In step 2, identification of papers was carried out using the 'Water-Energy-Food Nexus' linked keywords and the articles between 2015- 2022 were prioritized. Further, step 2 revealed a total of 9950 papers from the research platforms, out of which 7914 papers were identified from ScienceDirect while 2036 papers were identified from Google Scholar. In step 3, the collected literature was further identified and filtered using four filters: (a) Research papers, review papers, book chapters and conference proceedings (b) Peer reviewed journals with impact factor (c) The scope of journals that include Climate action, Sustainable Development Goals, COVID-19, Food security, Energy resilience (d) Papers that explicitly employ the nexus concept for management of the WEF sectors and the interaction between them. After the application of filters, 153 papers were selected for this study. The selected papers were analysed based on the classification criteria to

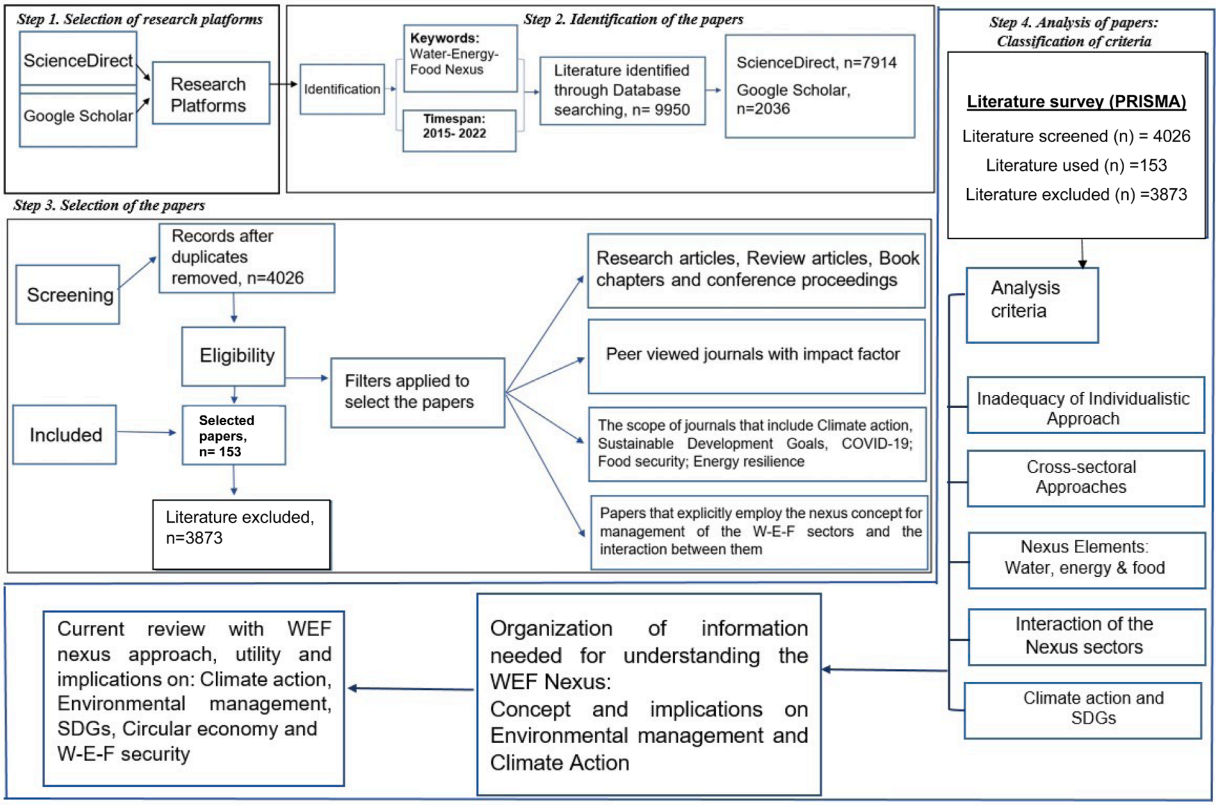

Fig. 1(a). Flowchart of the methodological process and novelty linked with present review.

empirically address (i) Inadequacy of individualistic approach (ii) Cross-sectoral approaches (iii) Nexus elements: Water, energy and food, and (iv) Interactions amongst nexus sectors (v) Climate action and SDGs (Fig. 1(a)).

The year-wise categorization of selected articles which ranged from 2015 to 2023 was conducted further in accordance with specific themes linked with WEF Nexus. In the year 2015, i.e., about 4 years after the conceptualisation of the WEF Nexus, an estimate of 112 articles on "Water-Energy-Food Nexus" were identified using Google Scholar platform, out of which 6 belonged to the category of review articles.

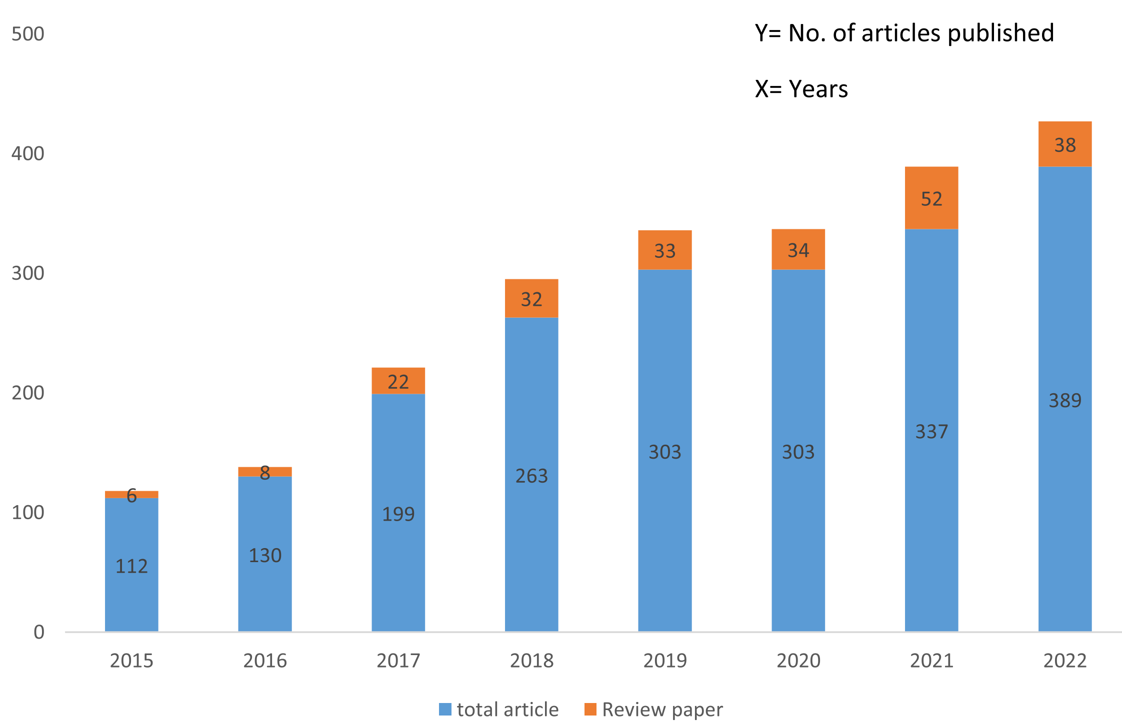

Fig. 1(b). No. of articles published on the topic that concerns Water-Energy-Food Nexus. (Source: Google Scholar).

However, the number of published articles increased along with the years as shown in Fig. 1 (b). To this end, the year 2022 saw the highest amount of articles written on the WEF Nexus topic, indicating that this integrated method and concept received wide recognition and constantly evolving over time. Although there is a growing body of literature on the WEF Nexus, there are still limitations in relation to applicability of nexus models for policy recommendations [42]. It can be helpful to comprehend how nexus issues have changed over time in order to build a sustainable framework for integrating WEF resources [43]. Out of the published WEF Nexus literature from Google Scholar, a few of them are linked with climate change and action as shown in Fig. 1 (c). In this respect, the year 2020 recorded the highest number of literatures that link the WEF nexus with climate change.

3. The water-energy-food nexus: concept and inter-related sectors

The word nexus was initially used in conjunction with natural resource management during 1980s in an UN initiative in order to establish a link between energy and food [8]. The term "WEF Nexus" was formally conceptualized at the Bonn International Conference, 2011 with an aim to give a solution for environmental challenges and pave the way to sustainable development [44]. The word "nexus" literally means "to connect" [45]. Since the emergence of the word 'nexus' in 2008, it has been widely debated, explored, and promoted in global scientific and regulatory Institutions. Water, energy, and food are inextricably linked, creating a policy nexus [46]. The term describes the interaction of two or more elements and attempts to assess whether they are dependant or independent with respect to each other. The WEF Nexus is the study of the connections amongst the three sectors, as well as the synergies, and trade-offs that arise from how they are managed, such as the interaction between water and energy; water and food, and interaction between energy and food [47,48]. The WEF Nexus has been proposed as a vehicle for moving civilization along a path that maximises the efficient use of natural resources such as water, soil, and energy [49]. In fact, the nexus emphasises non-linear system analysis and dynamic feedbacks across all sectors (Fig. 2). The inception of WEF Nexus was perceived differentially amongst professionals from global scientific and regulatory institutions [50]. The experts from energy sector refers to the energy-water-food (EWF) nexus, hydrologists and water engineers refer to it as the water energy food (WEF) nexus, while agriculturalists refer to it as the food-energy-water (FEW) nexus [51]. The conceptual approach to the WEF Nexus is often based on the perspective of the particular researcher or policy-maker, as evidenced by this variation in terminology [52]. The disagreement or research-centric derivation about the exact meaning and use of the nexus suggests that it is still a developing or gradually evolving concept [53].

The issues facing development are cross-cutting, and most resources are also transboundary in character [54]. Emerging cross-sectoral methods like WEF Nexus could be effective in this regard [32]. In natural resource management, the WEF Nexus is widely defined as a method that analyses interconnections, synergies, harmonisation, and trade-offs across water, energy, and food [36]. Further, the WEF Nexus is a significant instrument in climate change adaptation because of its integrated response to resource planning and sustainable environmental management. In this context, it is evident that during the initial years of the implementation of the nexus, the dominant conceptualizations in the existing literature were inherently depoliticized and fail to take into account the historical, social, and political trajectories pertaining to regulatory frameworks for water, food, and energy [55]. According to Foran [55], incorporation of social and political context can be done by recasting the Nexus with an explicit assessment of current water, food, and energy provisioning services [56].

4. Cross-sectoral approaches of the WEF nexus

4.1. Water sector

Freshwater reserves are sufficient to meet global demand, but uneven distribution and other factors have resulted water scarcity in some areas [57]. According to UN estimation, 1.2 billion people live in places with water scarcity while another 1.6 billion live in areas with economic scarcity [57]. In terms of water availability, 748 million people lack access to drinking water [58]. Growing demand, unsustainable withdrawal rates, degradation of source water quality, and changing climate patterns are all likely to exacerbate water resource depletion, both in terms of quantity and quality. Water scarcity has a direct impact on human consumption while it exerts indirect effects on energy supply,

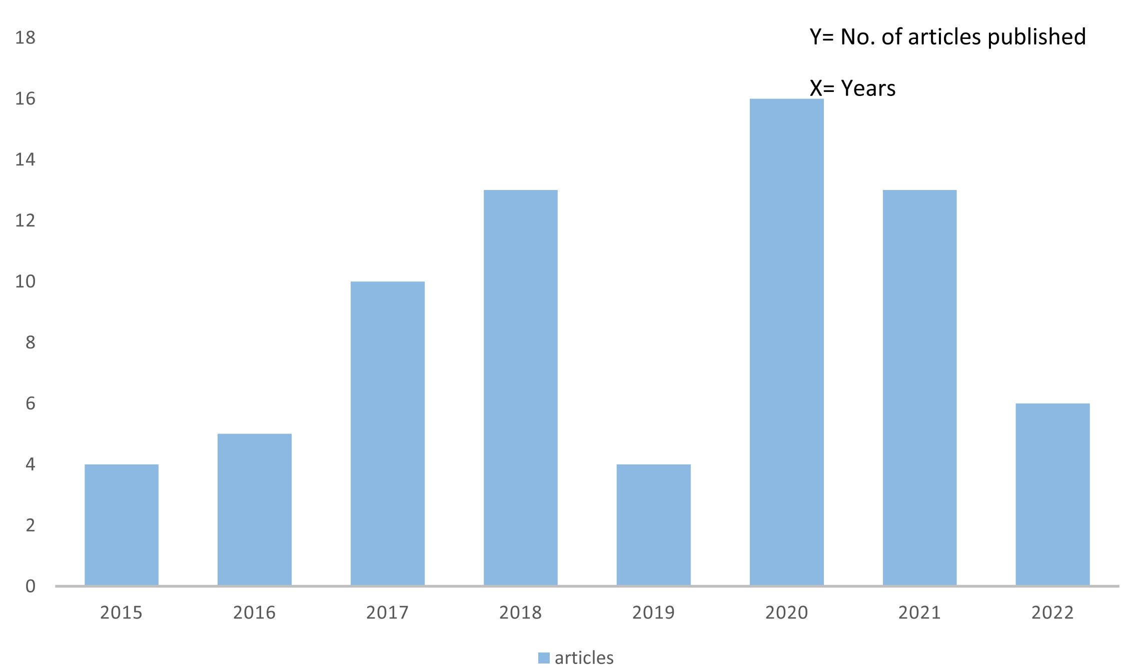

Fig. 1(c). No. of articles that link WEF Nexus with Climate Change and action. (Source: Google Scholar).

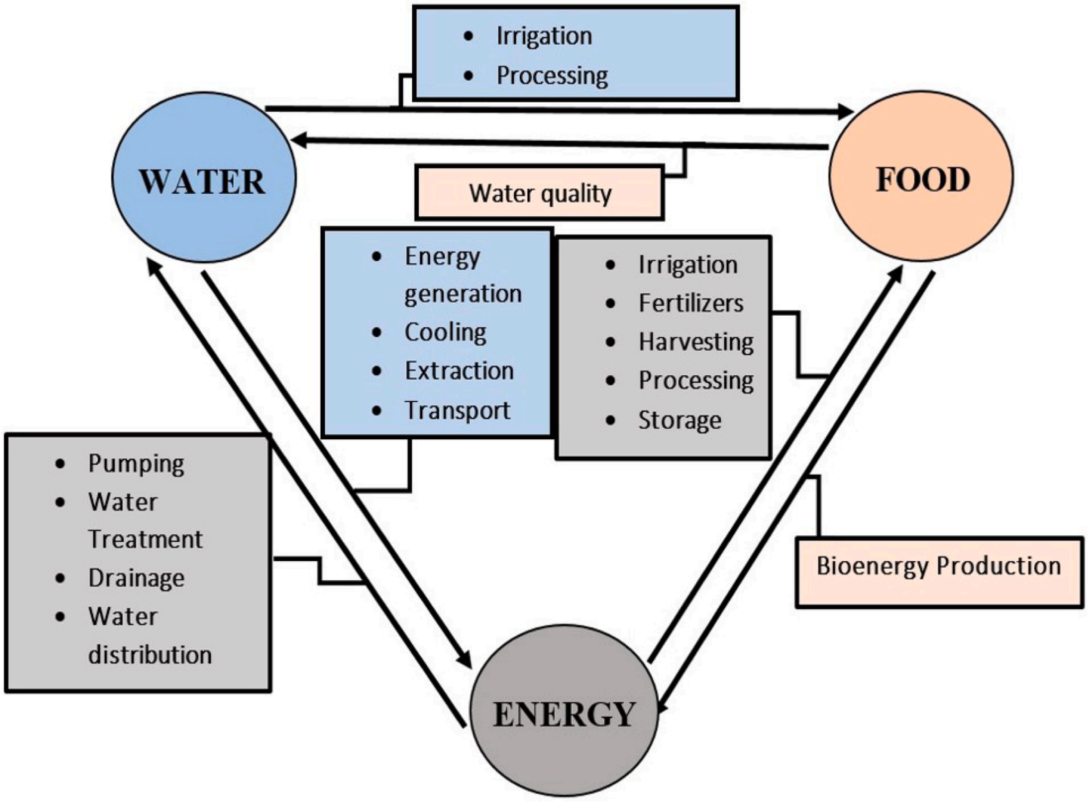

Fig. 2. Interconnection between the three sectors of the Water-Energy-Food Nexus with detailed non-linear processes that occurs between them. (modified and drawn after IRENA, 2015).

food production, and the ecosystem [59]. Technical barriers to water access in industrialised countries include problems with groundwater extraction and the degradation of surface water sources [60]. In recent decades, excessive groundwater withdrawal can have a variety of repercussions, including increased soil salinity, water stress, and vegetation changes [61]. Therefore, the Bonn 2011 Nexus Conference underlined the importance of the water sector in the nexus together with other sectors [44,62]. Nevertheless, placing the water sector in the centre of the nexus may jeopardize the initial goal of generating a clear cross-sectoral view and response alternatives that outperform typical sectoral approaches [63,64,50]. Water sector operations include water supply, sanitation and hygiene services (WASH), water resources management (WRM), irrigation, hydropower, and activities related in water policy making, administration, and management, as described by the SDG 6 i.e., 'clean water and sanitation' [65]. Future availability and demand can be bridged with proper site management, which unquestionably calls for effective governmental involvement.

In the recent years, WEF Nexus is adversely influenced by the outbreak of COVID-19. Water has a more significant impact on the spread and management of the virus than the other sectors of the nexus [40,39]. The institutional (e.g., World Health Organization) recommendation to routinely wash hands for preventing the transmission of infectious diseases stressed the water resources [66]. To this end, poor communities were usually deprived of adequate access to water and sanitary facilities, which made them more susceptible towards fighting the pandemic [67]. Moreover, COVID −19 outbreak stressed the world's water sector which may be tightly linked to other environmental challenges such as climate change, rapid population growth, aged and inadequate infrastructure, and poorly planned urbanisation [68].

4.2. Energy sector

Rise in energy demand is ascribed to multiple factors such as population expansion and industrial growth [69]. Despite the availability of renewable energy sources, fossil fuels are predicted to remain the primary fuel source, accounting for about 80% of total energy supplies in 2023. However, surge in renewable energy demand is observed in global landscape which is projected to grow in coming decades [70]. If this trend of exploring renewable energy options is sustained, then the use of coal is anticipated to decline in the majority of regions while oil demand will still be on the rise [71].

In 2019, total worldwide energy consumption was primarily divided into four categories [72]. To this end, 22% energy was utilised for electricity, 63% dissipated as heat generated from combustion of fossil fuel and hydrocarbon or oil products in engines [72]. Another 11% was consumed in household for cooking and heating in the form of biofuels, such as dung and wood and the remaining 3% was consumed as heat by other sources (Fig. 3) [72]. The energy consumption rate has changed slightly since 1995, incidentally in the similar time-span when first UN Climate Change Conference of Parties was held [73]. In recent perspective, the COVID-19 pandemic had significant influence on energy demand global CO_2 emissions, and global economy [74,75]. Therefore, in order to prevent the global warming, the global energy system must rapidly decarbonize [76]. In this respect, U.N. climate conferences predicted that the percentage of low carbon power generation increased only from 13.4% to 20.5% in last 30 years [62]. The share of low carbon electricity was high in 1995 (36%), however, this share has declined drastically over the years [76]. The challenges of multi-objective decision making in the energy industry are trade-offs between energy security, universal access to cheap energy services, and environmentally responsible energy production system and usage [77]. Recent findings indicate that the grim scenario of energy resources during COVID-19 pandemic has slowed down global progress towards achieving SDGs by 2030 [78].

A sudden change in lifestyle brought by the pandemic led lockdown has drastically raised the demand for electricity in residential complexes

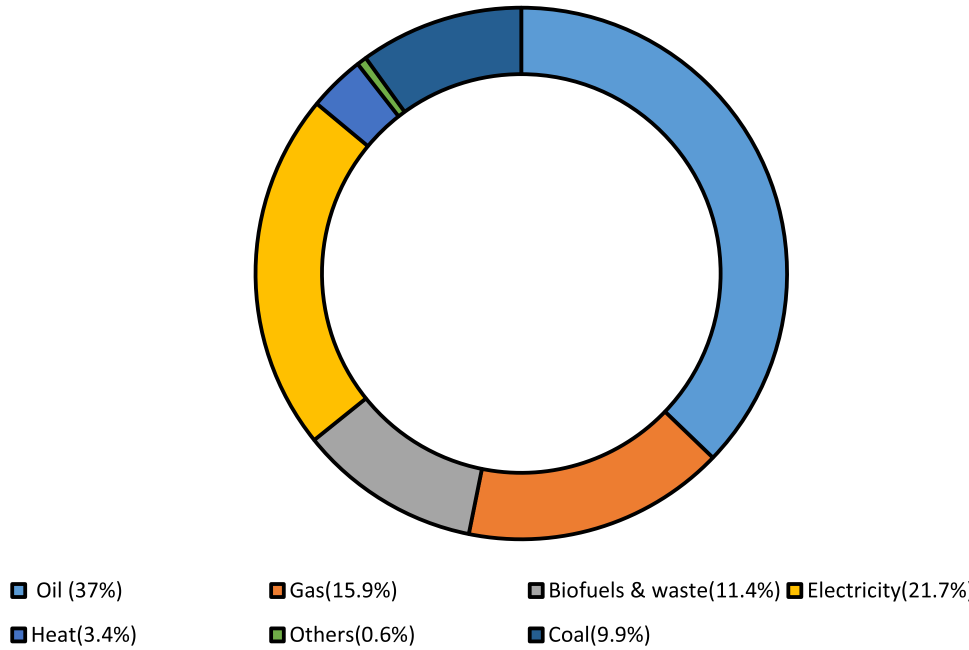

Fig. 3. Final Global Energy Consumption in 2019, data by IEA (2022). [53].

while succinctly decreased its demand in businesses and industrial sectors, which has an impact on the national energy demand profile [79]. In view of these aspects, the transition of conventional energy sources to sustainable and renewable energy systems must be accelerated in order to meet the SDGs [10]. To this end, the use of increased energy efficiency and renewable energy technology should be encouraged in rural areas by substituting fossil fuel subsidies [25]. In this respect, emerging nations must implement the fossil fuel subsidy swap in order to address the challenge of energy scarcity [80].

4.3. Food sector

Increased production of food is necessary to secure future nutritional demand, but simultaneously it's also crucial to sustainably utilise the existing amount of food produced [81]. It has been predicted that to sustain the food security of 9.1 billion projected population by 2050, food production worldwide should increase by over 70% between 2005 and 2007 and 2050 (see Fig. 4) [26]. In context of developing nations also, production of food needs to be doubled to achieve food security [82,83]. In addition to food security, upsurge in the production of global food waste is another challenge faced in recent times. Globally, nearly one-third (1.3 billion tonnes per year) of the edible portions of food produced for human consumption are lost or wasted [84]. Food waste can jeopardize the agricultural economy and food security [85]. Further, the disposal of food in landfills produces methane, thereby contributes significantly to GHG emissions [86]. Additionally, GHGs such as CO_2 is released from the processes involved in the production, handling, and transportation of food [86].The effective operation of food sector

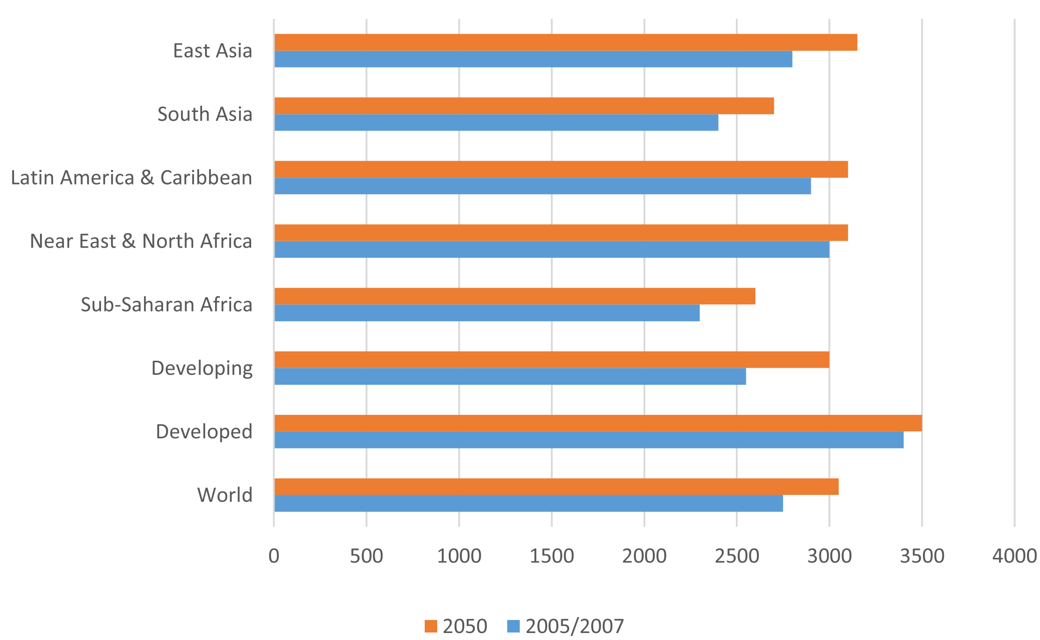

Fig. 4. Comparison of per capita food consumption of different countries. Data from FAO, 2017.

includes sustenance of agricultural production, livelihood protection of small scale farmers, and providing equal access to land, technology, sustainable food production systems, and resilient agricultural practices [82,83]. All of these goals are integral part of SDG 2 i.e., Zero Hunger. For most developing countries, achieving SDG 2 is critical since it contributes to environmental sustainability and economic prosperity [35].

The global pandemic influenced four components of food security such as availability, access, utilisation, and stability [79]. The COVID-19 epidemic has served as a wake-up call for food systems, which have been unsteady for decades [82]. COVID-19 crisis has remarkably altered food systems in terms of its effects on demand, supply, distribution of food, and consumer behaviour [7]. With outbreaks that have shut down multiple facilities globally, COVID-19 has impacted various activities in fisheries, livestock, agriculture, and their linked supply networks [83]. In post COVID phase, issues related with in-equitability of food sectors can be addressed by effective governance, emphasising sustainable food production and consumption, and employment to local agricultural workers to help achieve food security and SDGs (e.g., SDG 1 and SDG 2) [84,85]. Understanding sustainable food production systems and consumption patterns may be highly effective in addressing the adverse environmental and social effects of food wastes [81].

5. Interactions amongst sectors of the nexus

5.1. Water-energy interactions

Water and energy are inextricably interwoven and interdependent, as water resources accounts for 90% of worldwide power generation [2]. Furthermore, water demand for energy production is projected to rise by 85% over the next two decades and result in higher global water withdrawals [92,80]. This upsurge in water demand is an outcome of the global transition to higher-efficiency power plants with more advanced cooling systems and increased consumption in biofuel production [92, 80].

The amount of water used in the energy sector is variable and dependant on the energy harvesting technology, the source of input water used, and the type of fuel used [93]. For instance, thermal power plant is water intensive industry due to extensive operation of cooling systems [93]. Similarly, hydropower plants are entirely dependent on heavy consumption of water resources [94]. Hydropower plants are the major sources of freshwater depletion in the developed nations such as United States which utilise 41% of surface water [87]. It has been predicted that in the year 2035, worldwide energy demand is expected to rise by 35%, which may increase water requirement by 20% [88].

Biofuel manufacturing and biorefinery industries require more water resources when compared with fossil fuel-based goods [89]. Encouraging the biofuel industry in the transportation sector such as by providing subsidies has stressed land and water resources which were assigned for agricultural food production [89]. Extraction of water resources for multiple agricultural and domestic uses is also energy intensive process [90]. In this respect, desalination of seawater is the process which utilise more energy than those involved in extraction of surface and groundwater [91]. Multiple processes linked with water and wastewater treatment facilities are also energy intensive [88–90].

5.2. Water-food interaction

Agriculture is the major consumer of freshwater, accounting for over 70% of total usage [94]. Production, processing, and distribution of food crops demand excessive use of water resources. Water from the irrigated agricultural fields can be percolated and joins groundwater with fertiliser and pesticide contaminants [88]. Food processing and manufacturing industries potentially utilise water resources and simultaneously release wastewater effluent into the freshwater environment [95]. The production of edible crops for human consumption require excessive quantity of water which may be considered as the direct depletion of water resources. On contrary, the rapid increase in the global generation of the food waste can be considered as indirect depletion of water resources [96].

5.3. Food-energy interaction

Sustained production of the edible crops is necessary to achieve SDG 2 (Zero hunger), however, raising crops is an energy consuming process [97]. Hence, farmers are motivated to improve energy efficient devices with low operating costs to facilitate climate smart agriculture [98]. Agriculture is largely dependent on the energy sector which can be consumed either directly or indirectly [99]. The manufacturing of agricultural equipment and agro-chemicals such as fertilizers and pesticides can be considered as indirect utilization of energy in agriculture [100]. Whereas, the direct consumption of energy in agriculture is mainly subjected to the tube-well engines assigned to pump surface water for irrigation [100]. A substantial portion of agricultural production such as food processing activities are energy intensive, therefore wastage of food stuffs can be considered as energy loss [26].

5.4. Water- energy- food interaction

Food, energy, and water systems are interrelated in an intricate manner [101]. This complex inter-relationship is ascribed to simultaneous increase in demand for WEF resources in multiple sectors of agriculture and industries [101]. These linkages between the water, energy, and food systems can result in trade-offs but can also provide synergies depending on the formulated policies [102]. For instance, the water sector plays a significant role in the generation of electrical energy through hydropower plants and also in the production/cultivation of food crops through irrigation [103]. Hydropower plants are an ideal example of beneficial interactions amongst water, energy, and food sectors [104]. There exists multiple interactions between hydropower and other nexus sectors [104]. The hydropower plant impounded reservoirs can be utilised for addressing the food as well as energy security [104]. In addition to producing energy, the water stored in the reservoirs of hydropower plants can be used for aquaculture, agricultural irrigation, industrial activities, and domestic purposes [105]. However, trade-offs are often observed between hydropower generation and food production in certain cases where large scale crop cultivation are dependent on irrigated water system [64,106]. Similarly, the energy sector is widely utilised in the purification and supply of water [47].

Energy is further used in the machinery for harvesting crops, fertilisers industry, and as fuel (e.g. liquid petroleum gas) in the preparation of food [47]. Likewise, the energy crops from food sector has the potential to contribute to the generation of bio-fuel [107]. Perhaps, the most prominent interaction between food, energy, and water may be the production of first-generation biofuels [103,108]. Bio-ethanol and bio-gas can be synthesized from energy crops through fermentation and anaerobic-digestion [107,109). The majority of first-generation biofuels are produced from crops like maize and cereals that could be used as food resources [104]. For the large- scale cultivation of these crops, water and energy systems are involved intensively [109,110]. Further, the potential rise in demand of renewable energy like biofuels can indirectly elevate the prices of the key crops and thereby causing a trade-off between energy and food sectors [111,19]. This phenomena fosters competition between the food and energy sectors in view of raising edible crops for energy production [112]. The renewable energy produced from the water (e.g. hydropower energy) and food sector (e.g., bioenergy) contributes to climate action and SDGs as they help in minimizing the GHG emissions [113]. Furthermore, these renewable energy options can be employed to reduce the trade-offs amongst the sectors of the nexus [114].

6. Linking WEF nexus with climate change

The WEF Nexus is applicable to address multiple environmental challenges like climate change [115,116]. Natural resource depletion, economic expansion, urbanisation and industrialisation are inextricably linked with the climate change [44]. These interrelated framework of environmental challenges with climate change emphasized the need of WEF Nexus to attain environmental sustainability [117]. The need for the WEF nexus is further evidenced by the failures of sector-driven management approaches in addressing climate change [118]. Therefore, Al-Saidi and Elagib, (2017) predicted that climate change can be a crucial driving force for the WEF Nexus implementation [118].

In order to mitigate and adapt to climate change, it is anticipated that by 2030, the food production should rise by 50% and energy resources by 30% while there is an urgent need to conserve additional 30% fresh water resources (Fig. 5) [119]. Extreme weather events linked to climate change, such as droughts and floods have emerged as the most pressing challenges to sustain emerging economies. Climate change induced temperatures rise and shift in rainfall patterns will have profound impact with limited financial incentives for adaptation and resilience [120]. The World Economic Forum during 2011 released a significant report, alerting world leaders to the importance of examining the interrelationships between key global challenges [121]. Rising global temperatures significantly impacted the global water, food, and ecosystems. Rising sea levels and flooding will be most severe in the mega-deltas, which are critical for food production [119]. Global GHG emissions should be decreased by at least 50–60% by 2050 compared to current levels and WEF Nexus can play a crucial role in achieving this target [119]. WEF Nexus is in fact considered to be a socio-ecological systems approach to address climate change [54]. Extreme weather disasters (e.g., droughts and floods) is rather more frequent in present scenario which can influence agrarian based economies [40].

Renewable energy options such as biofuel is tightly linked to WEF Nexus and climate change, as their production requires natural resources to minimise GHG emissions [122]. In this context, Nzuma [123] has proposed several climate change adaptation strategies for the climate change hotspot or vulnerable regions, including (i) Promoting climate smart agriculture (ii) Developing Early Warning Systems (EWS) (iii) Integrated water resource management (iv) Promotion of low-carbon renewable energies and (v) Increasing monitoring and modelling capacities across each of the WEF sectors [123]. Also, in WEF Nexus perspective, improved transboundary natural resource management can facilitate climate proofing to accelerate the efforts towards climate action. Henceforth, implementing the WEF Nexus into environmental management policies can augment energy resilience and nature sustainability to facilitate climate action [123].

7. WEF nexus in environmental management and sustainable development

The WEF Nexus strategy uses pragmatic approach to facilitate logical, efficient, and balanced management of environment, natural resources, and socioeconomic systems [124]. The WEF Nexus method takes a holistic and multi-sectoral approach for promoting sustainable development and addressing the problems imposed by global environmental change [125,126,44]. As a result, effective Nexus management is required to accomplish the United Nations' SDGs [127,128]. Water, energy and food security are crucial factors of WEF Nexus and environmental management which can be addressed in totality through global institutional collaboration and financial incentives [129]. Anthropogenic disturbances and modern intensive agriculture significantly stressed WEF resources which impeded the progress towards achieving the SDGs and environmental management [130]. The COVID-19 pandemic has further impeded the progress of the SDGs, which need focused attention in the future studies [131]. Therefore, during COVID-19, building the institutional capacity and raising awareness about the constraints linked with WEF Nexus is required [132].

Past studies attempted to validate the nexus utility for integrated environmental management and sustainable development [134]. Additionally, Griggs proposed a more coherent environmental and social framework with measurable aims in relation to the SDGs [133]. Components of WEF Nexus inextricably relate to a distinct SDG, with potential to reduce environmental footprint [83,134]. In addition to SDGs, the WEF nexus also provides a broader framework for accelerating Circular Economy that includes improved design (redesign) and materials management (Fig. 6) [68,134,31]. The integration of WEF Nexus in environmental management policies can therefore significantly contribute to UN-SDGs, circular economy, and climate action which are intimately linked with the sustainable development [51,135] (Fig. 7).

The nexus approach's novelty is that it begins to address issues like land tenure, market access, and equity issues that previous approaches

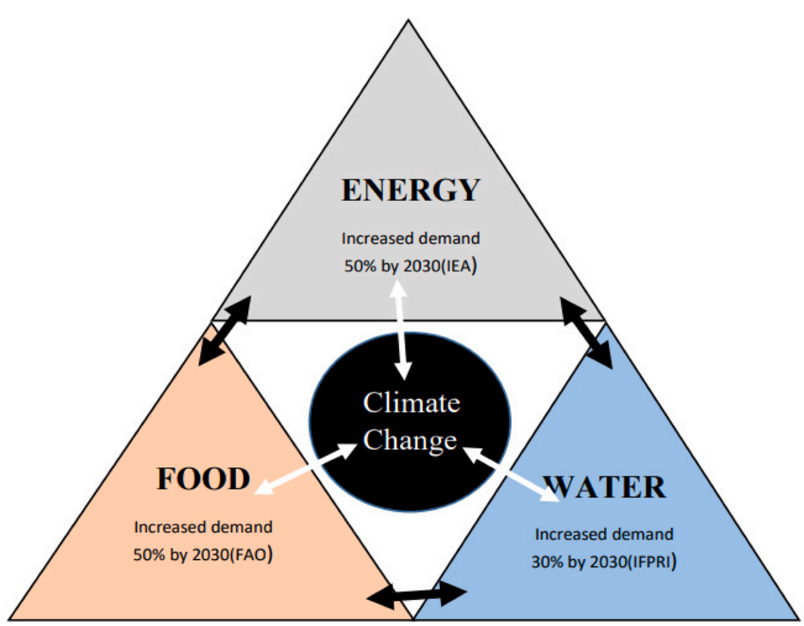

Fig. 5. Illustration of Beddington's Perfect Storm Scenario [46].

Fig. 6. Linking the WEF Nexus with the Circular Economy and SDGs (a modification of Wang et al., 2021 Credit (symbols): United Nations.

have overlooked, despite their interlinkage with environmental management [136]. The WEF Nexus concept can be implemented across many industries to achieve environmental sustainability. For example, farm efficiency can be increased by implementing sustainable techniques such as collecting rainwater, creating photovoltaic electricity, producing biogas, and bio-fertilizers [137]. These methods will reduce the pressure on non- renewable energy sources and provide reasonable solutions to achieve WEF security [137]. Probabilistic analysis and stochastic models are required to promote accurate nexus data in order to aid in risk management decision-making [138]. By taking into account stochastic components, this strategy may be able to decrease global risks and promote greater system integration [139]. WEF Nexus can help managers or policy makers to decide on the 'inside-out perspective' that include numerous examples of interrelated-issues [44]. Good governance can also be a vital factor in strengthening WEF nexus to help achieve sustainable development and environmental management [139]. Increasing financial incentives in technology innovation can also be helpful in accelerating the WEF prospects for attaining energy resilience and SDGs [45]. Promoting the collection, analysis, sharing, and discussion of multi-sectoral data on the WEF Nexus will help refine knowledge and offers empirical data to support environmental management [132]. Thus, cross-sectoral WEF interactions can sustainably manage the environment with explicit trade-offs and synergies [140,141].

8. Effects of COVID-19 on the WEF nexus

The COVID- 19 pandemic has significantly impacted the WEF Nexus and disrupted the supply-demand of associated resource sectors [35]. The impact of the COVID- 19 pandemic can be classified into direct and indirect impacts [142]. The direct impacts on WEF Nexus are the consequences of the virus spread or contamination into food and water matrices while the indirect impacts are the socioeconomic and environmental repercussions brought on by lockdown restrictions [142]. After the onset of the pandemic, upsurge in water consumption was observed due to hygiene requirements such as washing of hands, disposal and sanitation of COVID-19 treatment materials, and disinfection of containment zones [39]. In general, it was observed that water consumption has increased in the medical and household sectors when compared with the water demands before the occurrence of pandemic [143]. This increased use in water resources was due to lockdown induced stay at home and recreational activities like gardening [138]. On contrary to increased domestic uses, the demand of water in the industrial sectors was significantly lower during the pandemic than the pre-pandemic phase which was attributed to suspension of industrial activities [143]. Similarly, the energy sector also faced significant challenges as a consequence of COVID-19 [144]. Fluctuating energy demands were observed as immediate impacts of the COVID-19 [145, 143]. Before the pandemic, the industrial sectors were primarily responsible for the increased demand of electricity. However, energy demand was significantly decreased due to the pandemic driven industrial shutdown [146,147]. The global energy demand bounced back to the pre-pandemic phase after the relaxation of COVID-19 lockdown restrictions to revitalise the economic and industrial activities [146]. The COVID-19 pandemic brought several challenges to the energy sector, especially paradigm shift in their use pattern and associated environmental impacts [144]. Furthermore, the COVID-19 has adversely influenced the renewable energy sector due to the suspension of subsidies of financial incentives [147]. Pandemic effects were also noted in agricultural sector due to unequal access and distribution of food, especially to the marginal population [148]. According to reports, COVID-19 left rural residents in severe socioeconomic stress because they had limited access to indigenous food sources [37,40]. However, the global food consumption was higher during the pandemic as compared to the food consumption during pre-pandemic phase [149]. The pandemic restrictions on mobility adversely influenced the

Fig. 7. Impacts of nexus approaches on SDGs (a replication of diagram by Liu et al. [64]) Credit (symbols): United Nations.

employment, farmers' income, and rural livelihood [38]. Additionally, disruptions in agricultural exports affected the global food trade [150]. Food shortages and food waste across the supply chain were triggered by the COVID-19 pandemic, which further disrupted the food systems [151]. Furthermore, the COVID-19 pandemic has impeded the progress towards the achievement of the 17 SDGs [147]. The WEF nexus is inextricably linked with the SDGs and out of the 17 SDGs, 3 goals namely SDG 2 (Food), SDG 6 (Water), and SDG 7 (Energy) are widely influenced by the nexus [152]. In addition to SDGs, the pandemic has adversely influenced energy resilience, water resources, food security, and human health [3].

9. Conclusion

The WEF Nexus approach serves as a significant tool to manage the multiple sectors of natural resources and analyses the synergies and trade-offs amongst them. The nexus framework provides integrated water, energy, and food resource management approach to achieve major SDGs linked with human well-being. In addition to SDGs, the incorporation of cross sectoral WEF Nexus approach can augment the circular economy. The climate change adaptation can also be increased through monitoring and modelling capacities linked with multiple sectors of WEF Nexus. Facilitating renewable energies, sustainable water resource utilization, and circular economy can also augment the efforts towards climate action. The recent COVID-19 pandemic has a great deal of impact on the energy resilience, water resources, and food security. Thus, the deleterious impact of COVID-19 on the water, energy, and food sectors imposed constraints to achieve the SDGs. Nevertheless, an effective integration of WEF nexus in policy framework for environmental management and climate action can therefore help achieve the multiple SDGs for sustainable global development.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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