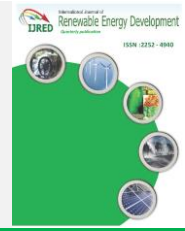




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Review Article

Water-Energy-Food Nexus Review for Biofuels Assessment

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Abstract. The appropriate use of limited natural resources for generating basic human needs such as energy, food, and water, is essential to help the society function efficiently. Hence, a new approach called nexus is being considered to resolve the effects of intrinsic trade-offs between the essential needs. A review of different methods and frameworks of the water-energy-food nexus was done in this article to give a detailed repository of information on existing approaches and advocate the development of a more holistic quantitative nexus method. Assessing biofuels under the water-energy-food nexus perspective, this review addresses the sustainability of bioenergy production. The results show the countries that can sustainably produce first-generation biofuels. Only a few methods have varied interdisciplinary procedures to analyse the nexus, and more analytical software and data on resource availability/use are needed to address trade-offs between these interacting resource sectors constituting the nexus. Also, "land" is suggested as an additional sector to consider in future studies using both the nexus index and life cycle assessment methodology. The review reveals that to tackle composite challenges related to resource management, cross-disciplinary methods are essential to integrate environmental, socio-political facets of water, energy, and food; employ collaborative frameworks; and seek the engagement of decision-makers.

Keywords: Food; Biofuel; Bioenergy; Water; Policy; Framework.

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1. Introduction

Biofuel production has experienced an exponential growth in recent years, and this can be attributed to both the unpredictable nature of fossil fuel prices as well as the recent energy policies by the EU and US directing that renewable energy should be relied on – as a source of energy – to some extent as a means to help mitigate the transport sector's greenhouse gas (GHG) emissions (Energy Independence and Security Act, 2007; European Union, 2009; Sorda et al., 2010). Global carbon dioxide (CO₂) emissions associated with fossil fuels usage surpassed 11,830 million metric tonnes in 2013 (Saboori et al., 2014). More so, predictions are that by 2030, the level of global transportation energy consumption and CO₂ emissions would grow by more than 80% (EIA, 2015). Presently, about 85% of global energy demand is met by combustion of fossil fuels that are exhaustible. From 2010 to 2025, an increment of about 50% is expected in global energy demand, with a big part of this increase coming from rapidly emerging economies. Amongst the most discussed talking points of scientific research in the present century

is generation and accessibility of energy (Sieminski, 2014). The concerns of researchers relating to energy accessibility and greenhouse gas (GHG) emissions can be improved by contributions from biofuels in countries dependent on importation of fossil fuels but having substantial agriculture; biofuels might sometimes be a better economic use of crops than for food (human consumption) as these crops would have less economic value (price) (Rulli et al., 2016). Biofuels utilized in transportation are of two major categories, viz., biodiesel and bioethanol. Bioethanol is derived or synthesized from starchy crops and sugar and is usually blended with gasoline, while biodiesel is derived from oil crops and organic fats and is usually blended with fossil diesel (Mosdale, 2008). The International Energy Agency (IEA) recommended that global fuels for transportation should have 27% biofuels by the year 2050 to achieve the global energy targets (Drews et al., 2016). Water, land, energy, and food are natural resources and major potential contributors to energy security because as renewable energy resources which can be harnessed continuously with proper management. Also, these resources are

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interlinked, thereby forming a cycle: Agriculture consumes energy and can also generate energy (as food for human consumption or biofuel crop). The generation of energy through hydropower and biofuels uses land & water resources, and sometimes results in competition with crop cultivation for food over scarce resources (land and water).

As stated earlier, the non-renewable resource depletion rate coupled with the ever-increasing cost of conventional fuels, energy demand, and climate change have been forcing us to look for multiple alternate energy resources. The search for alternatives to expand options of energy sources and to switch from the exhaustible fossil sources presently in use to replenishable sources (biofuels) has been the impetus for the significant interest in exploration pursuits to generate biofuel using starchy and oil food crops, namely, yam, cane, rice, palm fruit, soybean, cassava tubers, maize, etc. Lately, the use of non-edible components of starchy crops / food items - derived as unwanted portions from the processing of crops such as tuber peels, stalks, straw, and cobs – for the production of bioethanol has drawn attention. The utilization of biomass for energy (i.e., bioenergy) is considered to be a promising renewable energy alternative (Cherubini & Strømman, 2011). There is an increased attention across the globe in biomass energy networks, as proven by recent activities of the World Bank in many developing countries such as the Energy Sector Management Assistance Program (ESMAP) for the estimation of bioenergy potential (ESMAP, 2005; World Bank, 2016). To work in the direction of shifting the energy paradigm, natural resources (water, energy, land, food) are required, which are scarce and limited; excessive (unsustainable) withdrawals of these resources may jeopardize food security, stunt economic advancement, and create tensions within society (Hoff, 2011). The interconnections of these sectors have become more evident and the search for cross-sector efficiencies is very important to avoid unnecessary wastage of these limited resources. However, the management and use of these resources have historically been independent. This is apparent as past research works — crop cultivation and use, water generation and use, ecosystem well-being, socio-economic welfare, land use management and governance — show a sectorial topical focus which has often emerged in isolation. Consequently, a thorough and comprehensive review of executed and envisioned nexus approaches to recognize ideal schemes, enhance availability and encourage further advancement in frameworks for the evaluation of the nexus is a paramount need (Keairns et al., 2016).

As a remedy to the single-sector approach, scholars have called for a holistic approach to jointly harness the water, energy, and food (WEF) resources, and to easily recognize unplanned impacts within the involved sectors (Bazilian *et al.*, 2011; World Economic Forum, 2011; Mukuve & Fenner, 2015). Identifying the connections across the major natural resource divisions, and collectively boosting the efficiency of these sectors was a productive strategy for human welfare and sustainability with regards to resource and environment for the current and more importantly, upcoming generations. This is commendable; however, effectively putting them to action requires a nexus framework that is simultaneously

ecological, socio-economic, and political. Being a theoretical approach, the structure of the nexus takes the interpretation coupled with the understanding of the interdependence between the water-energy-food to enhance cohesive policymaking as well as improve sustenance. Nexus approaches and methods necessitate successful cross-disciplinary cooperation, but also a distinct comprehension of parts involved in certain WEF research – to avoid unplanned impacts that the approach was designed to cut off. The nexus concept has been widely accepted as the outcome of the previous economic and single resource sector development approach has been proved to have detrimental effects on the environment, consequently jeopardizing sustainability goals as underlined by research papers and outreach activities including reports of the Intergovernmental Panel on Climate Change (2014), Millennium Ecosystem Assessment and World Resources Institute (2005), and Rockström *et al.* (2009). The nexus idea also gained from trials to develop the concept of the Sustainable Development Goals (SDGs), and which was made prominent at the planning stage of a conference on Sustainable Development which took place in Rio de Janeiro in June 2012 (UNEP, 2011). The nexus idea was publicized through events and conferences such as the report from the FAO and Bonn 2011 on nexus and its related research literature (Hoff, 2011) and the Global Risks 2011 reports of the World Economic Forum (2011).

The nexus term needs a clear definition and, at this juncture, it is imperative to state what the nexus entails as well as highlighting some of the approaches that have been employed to analyse the nexus. Sanders (2015) also reported that the interlinkage amongst energy, food and water resources is generally referred to as the water–food–energy nexus. The nexus system is proving to be significantly more useful than the singular-sectored methods in effectively coordinating the consumption of these finite resources (food, energy, and water) as it avoids excessive exploitation of the constituting resource, which is made possible by its systemically linked framework, and its quantifying tools. An evidence to this claim is that the nexus framework is increasingly being recognised by several reputed international institutions as essential for policy making (FAO, 2018; EU, 2018). This study intends to draw up how these practical and conceptual holistic nexus methods such as the nexus index, life cycle assessment, dialoguing, material flow analysis, etc. have analysed and enhanced the interlinked resources of the nexus.

It was discovered from the reviewed articles that the nexus approach was used to tackle complex targets. These were targets relating to increasing resource productivity, assisting policy integration, and encouraging sustainable consumption of resources. A significant number of the studies assessed cited resource management and policy integration, while sustainability was mentioned in a quarter of them. Overall, the nexus approach results in effective management and allocation of resources as it is a robust means of accommodating the links and exchanges between water, energy, and food (De laurentiis *et al.*, 2016; Giupponi & Gain, 2016). Although many explanations on the WEF nexus have been given in literature, the outcomes of this literature review shows that the nexus

idea is largely used to arrive at mutual gains for the involved resource sectors and socio-economic benefits.

The focus of this review analysis is on the creation of the nexus as well as the linkages and interconnections among the water, energy, and food (WEF) systems. The fast green-revolution agriculture, especially in irrigation intensive food-producing regions highlighted the interactions among energy and water for agricultural production and food security and thus drawing interest of researchers.

Several countries in different continents all over the globe have executed and postulated various nexus connected projects, research, and conferences. Following the early attention in innovative research and practice of the nexus concept, reports from the World Economic Forum and Hoff (2011) proved instrumental as they help the nexus thinking gain attention of renowned institutions globally (World Economic Forum, 2011). Hoff (2011)'s research was drawn up as a concept summary of the nexus conference Bonn2011; major participants and donors of this conference were the United Nations, international policy brain-trust, and essentially, international financial institution. This attempt is indeed conceptual, with regards to water, energy, and food, helping to enhance the ecosystem services, urbanization, globalization, the burgeoning energy security topic, and with the two-pronged development objectives to strengthen green economy (agriculture) and poverty eradication.

On the practical front with regards to research, policies and implementation, the potentials of the nexus have not been fully harnessed to spot and reduce trade-offs at consumption and production phases. Even so, the nexus approach has been further extended from its initial in-out connection concept to an extensive footprint concept which factors in and details energy consumption for carbon reduction and climate conditioning. A couple of nexus studies examined supply value-chains of food and control/handling of waste as detailed in Vlotman & Ballard (2014) and Villarroel Walker et al. (2014). Some studies of the WEF nexus contribute to literature of trade-offs resulting from decisions to grow certain crops and for specific purposes; for food or biofuels, an example of such literature can be found in Moioli et al. (2016). Conceptualization of the nexus has been extensive, but it has not been reinforced by the development of assessment tools for evaluation of the nexus. Rather, more variations in methods have been created as an extension of existing conventional approaches, e.g., soil-plant water assessments, economic supply-chain analyses, and efficiency analysis based on engineering process studies. These approaches only provide a confined view of the relationship between the resources of the WEF nexus, with little potential to thoroughly explain the interlinkages resulting from the multi-sectoral nature of the nexus, hence portraying a fragmented nexus concept. This paper builds on the conventional literature considering policy documents that have thoroughly examined methods of the WEF nexus.

This review paper intends to satisfy two purposes. Firstly, a stock of WEF nexus research over the past years was undertaken. This was done to comprehend, how scholars and researchers studied the interactions of the WEF nexus, what are the promising approaches, and how identified challenges have been addressed. Secondly, this

review aims to identify the research gaps for further study to help solve issues of managing limited resources for the sustainable development of the most pressing needs such as water availability, food security, and biofuels development. A quantitative and evidence-based approach was utilized in this literature review.

2. Methodology

To comprehend the fundamental scientific literature, sourcing for scholarly communities and identifying connections within these literatures is important (Small, 1997). To plot the connections between the WEF nexus research writings, an exploratory investigation of published reports in the past years was developed. Search strings in Google were used which yielded important and a good number of publications. The search phrases were constructed over many repetitions using trigger words to incorporate several WEF nexus research themes. The nexus concept is important to this study because it thoroughly acknowledges the interlinks between resource sectors which is a lever for sustainability, and as earlier mentioned, this study intends to identify gaps within the nexus concept that can be explored to enhance sustainability. Citations of about 203 was arrived at from the "food and energy and water and nexus". The following criteria was employed to select articles: (i) the articles thoroughly engage the nexus idea to analyse the relationship between resources to achieve overall sustenance; (ii) the articles include at least two elements of the WEF nexus; (iii) the articles recommend systematic tools for WEF nexus assessment. To further refine the search for relevant studies, only peer-reviewed research papers were included downsizing the list to 107 citations (a little more than half the initial 203 citations). However, for the sake of brevity whilst not compromising on quality, this review further prioritised assessing articles that are most recent; thus 42 of these 107 citations were reviewed in detail. Analysis and synthesis then followed, which included the categorization of shortlisted study considering the following aspects: goal, concept, nexus assessment method, and additional analytical approaches. An objective of this review study is to understand the nexus approach (the nature of the relationships among the three elements) as well as give due account on the need of implementing advanced holistic nexus methods. These proposed holistic methods will help create room to improve (ease) the nexus evaluation and for the nexus to solve more intrinsic problems giving attainable results. The other objective is to identify the importance, if any, of the water-energy-food nexus approach.

3. Result

It is observed that diverse nexus projects are widely spread-out in various regions across the globe. A nexus project carried out internationally is termed a research found in every continent. It was found in this review that four nexus themed research works were carried out intercontinentally: water-food nexus had two projects, water-energy and water-energy-food had one project each, and climate nexus had two. Africa and North America tended to centre their attention on three nexus types, water-energy-food, water-energy, and climate related.

Other regions showed a more general interest in each nexus category. The reviewed papers revealed keywords as classified as follows; Water-related keywords were the most frequent ($n = 118$), followed by those related to energy ($n = 43$); watchwords related to climate were the lowest ($n = 7$). Four kinds of nexus were identified amongst the selected research works ($n = 42$): 6 articles had topics which were water-food nexus themed, 3 articles water-energy, water-energy-food ($n = 30$), and climate-related ($n = 3$). The highest number of projects was the from water-energy-food nexus, which accounted for over 70%, second highest was energy-food nexus with about 15%, water-food and climate related nexus accounted for about 7% each as shown in Table 1. The following section provides more details and discussion on the nexus types.

3.1. Details from different nexus approaches

This literature review revealed that there was a lack of clear and standardized tools to help examine the networks of the WEF resources. The review identified a good number of “water–energy–food” models and frameworks representing the past and present thoughts on integrated natural resource planning. It is imperative to state that only models that integrated at least two of the WEF sectors in the nexus were included in this review. These chosen models propound rigorous instruments, the approaches employed were assessed, and they mostly focused on formulating holistic models. The approaches and tools found in selected literature were all critically assessed research, accepted, and circulated by prominent non-governmental organisations such as the Food and Agriculture Organisation of the United Nations (FAO) and the International Water Management Institute (IWMI). The nexus approach is a very good way to show how and where the three resources (Water-Energy-Food) interrelate (Hanlon *et al.*, 2013). A handful number of articles concentrated on connections between crop cultivation for food, use of land, emission of greenhouse gases using different analysis of the three nexus elements, e.g., Energy–Food nexus articles by Fargione *et al.* (2008) and Searchinger *et al.* (2008). Water and energy are the most crucial needs of agriculture; hence, a major water and energy consuming human activity is food production, and there is a need for increased food production in decades to come to support the world’s rising population (Abunnour *et al.*, 2016). A principal concern of the water, energy, and food interrelation is water scarcity. Food production will be adversely impacted by the rising deficiency of water, indirectly this water shortage affects food production as water is also needed for energy production thereby creating contention, this in essence creates trade-offs between the involved resources sectors (Gulati *et al.*, 2012).

A water & energy nexus study in Spain which was performed by Hardy *et al.* (2012) introduced the significance of the nexus to provide a country-focused survey of the multidirectional responses which affects consumers and all sectors including the water management scheme. Two approaches to the consumption pattern of water in Spain’s irrigation activity which were energy related and the water-related energy sector, have been considered with an idea of first-generation biofuels

as a sustainable alternative or substitute to conventional transport fuel in Spain. The water-energy nexus (WEN) tool was also applied by Lin *et al.* (2019) to examine urban water and energy management. The WEN tool was used to identify the synergies, also with the help of this tool, assessment was carried out on the consumption efficiency measures of the WEN.

A model of Climate-Land-Energy-Water, referred to as CLEW model, got formulated by unifying 3 different tools for analysis, viz., Energy framework (LEAP), water framework (WEAP), and Land-use framework (AEZ). This CLEW nexus approach is a practical one to integrate assessment for selected sectors with strongly interlinked issues. Through various watershed regulatory conditions, water use, availability, infiltration, overflow, crop water requirement, circulation, storage, including in-stream water quality with differing watershed and regulatory conditions were estimated using this tool (Sieber, 2019). An advantage the WEAP presents is the innovative resource management tool which gives room for comparing and measuring demand, supplies of water and makes predicting demand possible. This modelling framework models all resources including biomass, water, energy, and climate. Several models have been formulated and used in areas which are appropriate for certain purpose because a robust tool that can fit all WEF analysis and policy intervention is still lacking. A global regulatory model that encourages dialoguing was formulated by international water management institute, this model serves as an informative scheme management tool to address exchanges and subsequent water demands at the country level (IWMI, 2012).

An analytical nexus tool that studies the interconnections between water, energy, and food was formulated more than a decade ago. A holistic look on all areas of the nexus gives comprehensive details on resource shortages & productivity, and on prospective means of achieving sustainability in several locations (Hoff, 2011). With the purpose of moving the assessment from analytical to practical for on-ground implementation, several approaches have been used by researchers to assist the nexus assessment’s conclusiveness while also providing an all-inclusive framework that finds solution to issues that are peculiar to a certain site. Hoff (2011) provided literature on the potential improvement ways, also highlighting policy recommendations. This brings to our knowledge that the availability of these WEF resources (water, energy, and food) and their productivity differs greatly between regions and production practices which are addressed by nexus models. Enhancing the transition to sustainability is a possibility by using the nexus approach to explore means to reduce imbalances and derive extra benefits associated with a strengthened cohesion between sectors. These models can be implemented on country level to yield nation-wide benefits hence, these should entice every civil and governmental parastatal to partake.

The World Economic Forum presented another approach to the WEF in 2011 which aims to assist policymakers comprehend potential issues which will help the policymakers in responding swiftly in times of crises. With regards to the WEF nexus, several environmental risks were considered, such as climate change, biodiversity loss, air pollution, flooding, etc. Resource

security is an important aim to achieve as it directly affects the economy and would signify failure in governance if these resources run short according to the World Economic Forum's WEF framework. Furthermore, the World Economic Forum's blueprint incorporates environmental constraints affecting the nexus, such as population and economic growth. Also, it identifies areas to delve into and examine as levers, as well as coherent resource groundwork amongst multi-stakeholder, and providing infrastructure for managing the nexus (World Economic Forum, 2011).

The FAO's WEF nexus presents a new approach to achieve sustainable agriculture and food security (FAO, 2014). FAO's WEF Nexus framework is created with the recognition of the general discussion on sustainability vision across all sectors, e.g., agriculture and food. Food security is defined as the state in which "all people at all times have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active, healthy life" (FAO, 1996). Achieving food security is a target for the organisation as also serve as a node of entry for the FAO work on the WEF nexus. With the purpose of comprehending the interactions between water, energy, and food chain and links with human resources, the FAO formulated a nexus assessment approach, this approach also evaluates the performance of a technical or policy intervention in this context. The highlight of this FAO WEF nexus approach is its holistic vision of sustainability which makes attempts to balance between the different goals, needs of people and the environment. The Food and Agricultural Organisation of the United Nations (FAO) formulated an integrated analysis of societal and ecosystem metabolism framework which aimed to assess patterns of metabolism of socio-economic systems by giving a description at various levels and scales of socio-economic activities and ecological constraints (Giampietro et al., 2009). The analysis of the nexus was done by applying the framework with respect to different factors such as greenhouse gas emission, demography, and land use changes at the national level. This framework simultaneously describes and detailed WEF resource links and their interrelations of a complex system interacting with its environment (Giampietro *et al.*, 2013).

Some working areas were identified by the FAO to help manage the nexus interactions while being conscious of the effect of any alteration in the form of large-scale investment, policy decision, or change in farming practice which it could possibly have besides its original aims. The identified working areas are a) evidence, b) scenario development, and c) response options. Furthermore, the multifaceted connections involved in human and natural resources were thoroughly addressed by the FAO WEF nexus approach. The natural resource entails both biophysical and socio-economic resources, which provides our daily needs. The interactions of the WEF nexus tells us how these resources are used and managed, illustrating interconnections, impediments, and coactions (Weitz et al., 2014). The data-oriented workshop of the resource systems of the nexus as well as developing condition-specific targets and feedback options are done using the participants' consultative platform. These discussions and consultations assist in thoroughly addressing the common goals, interests of all stakeholders involved as well as help

resolve differences. The dialogue brings attention to the intertwined nature of resources and helps foster common interest for all participants and contributor. The evidence-based analysis of the FAO Nexus approach gives it a practical and on-ground advantage as this helps bring forth much needed data to address and pinpoint imbalances between different resource usages and to foster solution-driven thoughts.

The WEF nexus presented by Bach et al. (2012) proposed a robust watershed view of upcoming development choices. In addition to these basin perspectives, key agents that impacts the nexus and means of resolution in various basins in India, China and Winnipeg were summarised by Lawford et al. (2013). The WEF nexus was utilized to give analysis on alternative energy such as hydropower generation, biofuels, and desalination of water, whilst not neglecting the trade-offs on food security. Also, Miara et al. (2014) used the tool presented by the WEF nexus for assessing and planning algal systems.

Due to the competition caused by the production of bioenergy using basic resources; land and water, a study in Brazil by Benites-Lazaro et al. (2020) assessed regulatory measures and topics with connections to the basic limited resources (water, land, and food) in the production of bioethanol from sugarcane, and the problems of unifying the resources. This study analysed a significant amount of data collected over a period of 10 years from official and administrative reports, the dailies, and reports from other organisations that are not associated with the government by merging an individually probabilistic Latent Dirichlet Allocation (LDA) model with sentiment analysis. This analysis discovered that the WEF resources were being administrated as separate entities by independent administrative bodies. To arrive at sustainability in resource use, sugarcane production expansion must be reviewed and examined by administrators and stakeholders, utilizing a broader administrative nexus framework. In the same vein of promoting the nexus approach to achieve sustainability to help solve the challenges of achieving food security, meeting water and energy demands for a fast-growing population (Rasul, 2016), it further underscores that understanding the interactions of the sectors and strengthen their collaboration can be achieved by the nexus approach. Since this necessitates a significant change in decision-making toward a more systemic approach and the creation of frameworks to combine the activities of disparate actors and improve coherence and synergies within the three sectors, a plan for cross-sectoral cooperation to address these transboundary problems is proposed. Similarly, Giupponi & Gain (2016) aimed to manage the WEF nexus linkages and trade-offs to achieve effective resource management. It provides a systematic indicator-based approach for assessing water, energy, and sustainable development, with regard to the United Nations Sustainable Development Goals. The proposed model intends to provide a system that monitors improvement, compare various geographical areas, identifying potential faults, strength among and within the three dimensions of the WEF Nexus, and providing support for better management plans to accomplish its objectives. De Laurentiis *et al.* (2016) evaluated the WEF Nexus by taking into account the interactions between resource

systems, as well as the coaction and exchanges arising from how the resources are managed, which is a necessity for the proper implementation of these pathways. It goes on to explain how Life Cycle Assessment (LCA) could be used to produce the evidence needed to promote such desired improvements in food production and consumption trends.

Liu *et al.* (2017) delved into the problems encountered by the nexus approach. Although progress has been achieved, scientific research challenges on the WEF nexus still abound, also the use of this tool as a management tool is at the preliminary phase. To tackle challenges, it is important to highlight them, and they are stated as follows; insufficient data, absence of a quantifying tools to execute the nexus concept, unexhaustive database for comprehending the WEF networks. Formulating research procedures that examines the exchanges holistically as well as develop a tool to ease decision making to tackle them are essential to reduce financial uncertainties, and optimize monetary profits (Howells *et al.*, 2013). Monetary values and non-monetary values embedded in synergies and trade-offs involved in the water, environment, and pollution nexus are generally difficult to assign a price to. Conventional research methods do not often treat issues arising as a result of the association of resource sectors as judgements made in a nexus phase can proportionally tell on the options that will prevail in the other sectors. Liu *et al.* (2017) aimed to assess the WEF nexus' complexities in developing an integrated modelling approach, in doing this, it gave a background account of literature from stakeholders. The nexus setbacks identified were the absence of a systematic tool that could address all trade-offs associated, and the absence of considerable amount of data. Thus information-oriented research is needed to reinforce the database. Consequently, it is imperative to develop integrated software and instruments for standardized analysis of the WEF nexus.

Some of the connections of the WEF nexus was explained at a high-level of aggregation by Bazilian *et al.* (2011) mainly from a developing country perspective and through case studies, to arrive at some promising pathways for addressing the nexus. The challenges of comprehending the WEF policy interactions and addressing them holistically seems tasking. To address this challenge - which is still sparse -, important steps towards grasping the WEF nexus is to formulate holistic analytical tools, suitable algorithms, and extensive data sets that can futuristically forecast data energy use, water, and food (Chaudhuri, 2003). Bazilian *et al.* (2011) succinctly delves into standard methods of material flow analysis, life cycle analysis, operations research, complexity theory, and sustainable supply chains. Additionally, they also give the characteristics of a modelling framework that solely tackle the nexus and can effectively improve national policies and regulations.

The mutual interrelationships between WEF are diverse and handling them as singular sectors would not yield the intended results, hence they should rather be treated together; their interconnection is mostly mentioned as water, energy, and food nexus (El-Gafy, 2017; Rasul & Sharma, 2015). To harness the interrelationship between these sectors, the research on water–energy–food nexus carried out by El-Gafy (2017) is

an initial step to examining the decision making in formulating and evaluating national strategies. The purpose of the El-Gafy's research is to provide a method for the decision makers to analyse the water–energy–food nexus of crop production on a national scale and carrying out a quantitative assessment. By the suggested Nexus Index approach, indicators to evaluate the water and energy consumption, mass productivity, and economic productivity were recommended. With the help of these indicators, the Water-Energy-Food Nexus Index (WEFNI) was calculated which can be employed to develop schemes for the effective cropping practice to minimize resource consumption while simultaneously maximizing yield (productivity). The WEFNI can be employed as a holistic tool to assess the advancement in resource use and national agricultural plan.

Furthermore, with the aim of assessing the global sustainability of bioenergy production under the nexus by the means of a new efficiency type index, studies in literature employing the nexus index scope and methodology were analysed. This index was used to explain how and how much resources are consumed for biofuel production. The nexus index was implemented in several countries to assess the effects of biofuel production on the WEF resources. The nexus index results show the quantity of resources consumed for the production of these biofuels for every country where the nexus index was applied (Moioli *et al.*, 2018). Evaluating each component (individual resource) of the nexus index helps to identify the indicators that are less productivity and ways to arrive at desired improvements can be proffered to maximize resource use. Hailemariam *et al.* (2019) carried-out a study similar to the one mentioned above to analyze the (WEFN) in Ethiopia's sugarcane production market. The set of indicators used in prior studies, which considered consumption, mass, and economic productivity of water and energy, were used in this study. To identify and compare the WEFNI efficiency of the study sites, an integrated index called the 'water–energy–food nexus index (WEFNI)' was measured. The findings helped in the comprehension of the water–energy–food (sugarcane) interlinks. It also reveals that the increased energy usage at one of the farms as a result of the new irrigation technologies applied could be duly balanced by the reduction of water depletion and productivity growth, resulting in an increased WEFNI ranking. Recommendations were made to boost the WEF nexus of sugarcane production, such as the introduction of new irrigation methods and the replacement of fertilizers with filter cake. This research assists farmers and stakeholders to better understand their management output and taking steps to increase production, profit, and resource management. A study by Jaroenkietkajorn & Gheewala (2020) employed both the WEFNI method (El-Gafy, 2017) and WEF method (FAO, 2014) to analyse the water, energy, and food interrelationship to produce oil palm in Thailand as the promotion of biofuel has fostered an increment in biodiesel derivation from palm oil. Therefore, it is essential to maximize the production of this crop as it also serves as food for human consumption; to do this, all resources needed for its production needs to be holistically brought together and efficiently managed to avoid trade-offs. However, the study incorporates complete aspects including various other environmental aspects. The

interconnections between the energy, food and water for crop cultivation method was introduced at the national level in measurable terms by El Gafy (2017), while the FAO WEF nexus evaluation provided nexus-related procedures such as policy, planning, strategies, and interventions.

Ngammuangtueng *et al.* (2019) introduced an approach to holistically analyse the water, energy, and food nexus for rice cultivation and production at watershed scale employing material flow analysis (MFA). The use of a pictorial representation called the Sankey diagram made obvious how resources flow within the rice production scheme and how the sectors within the watershed boundary interact. To fit the local scale, a framework was formulated which can be tied to both national and world scale rice production grids. This research showed the benefits of utilizing the material flow analysis method to depict the connections of the WEF and its correlation with the selected metrics to measure water, energy, and food sustainability in the areas of resource usage productivity and financial evaluation. With the aim of examining the principal impacts of biofuels on food security, Silalertruksa & Gheewala (2018) investigated the water-land-food nexus in terms of its interlinks with land appropriation and water resources consumption. It provided a global appraisal of crops used for biofuel production; the results also gave rearranged global patterns of biofuel crops and oil trade. It also established the required or amount of consumed resources (land, water) to produce biofuels. Also, a study by Cai *et al.* (2018) showcased the interlinkages and relationship within the WEF resources from three perspectives which are the interlinked processes, the input-output connections during resource production, and the interactivity between markets, institutions, and infrastructure. The study surveyed the importance of the present practices and methods of the water community and current research gaps, to comprehend WEF procedures and execute its innovative corrective ideas using technology, infrastructure, and policies.

A study by Ghani *et al.* (2019) employed the Life Cycle Assessment (LCA) approach to evaluate footprint indicators and energy performance of bioethanol from the WEF nexus. The Life cycle approach is a standard tool and has been employed in several nexus studies for assessing potential environmental impacts throughout the production-consumption chain giving essential information on environmental impacts to support government policy (Albrecht *et al.*, 2018; Zhang *et al.*, 2018). A study by Yuan *et al.* (2018) also made use of the LCA approach. Besides assessing the environmental impacts from the sectors of the WEF nexus using LCA, it also provided a comparison of bioenergy and conventional energy for generating electricity. A spatial optimization model was suggested for examining the WEF nexus trade-offs within bioenergy production, food production, and environmental impacts giving a comprehensive perspective on renewable energy development. Besides using the suggested optimization model to address food, energy, and water security, it also concurrently considered climate factors under the climate change scenarios of the Intergovernmental Panel on Climate Change (IPCC). According to this evaluation, a resourceful WEF assessment framework was developed for choosing

suitable food, energy, and water policies to meet local demand and concurrently reducing environmental impacts. Mekonnen *et al.* (2018) assessed the life cycle greenhouse gas emission as well as other indicators (footprints) from the production of bioethanol. It also examined the energy performance of bioethanol from molasses. The findings of this research were presented in four footprints associated with the production and use collected during its life cycle. The sugarcane cultivation phase was found to contribute more to these footprints than the other phases of the life cycle.

As the focus of this paper is biofuel development through the WEF nexus, we took a dive into biofuel WEF nexus papers. Several authors have examined the WEF nexus and many indicators are available to analyse the effect of first-generation biofuels. It is worthy to state that there are differences between the first-generation and second-generation biofuels production in terms of resource consumption such as water use and depletion, competition with food, and land consumption. These differences help in making vital decisions to avoid competition for these limited resources. This comparative analysis helps to highlight quantified resource requirements to produce these biofuels. For example, quantitative indicators of land and water use for biofuel production have been used to assess the impact of bioenergy production of various resource sectors (Ngammuangtueng *et al.*, 2020; Rulli *et al.*, 2016). Although, only a few trials of analysing the interconnection between the WEF for biofuel production have been carried out, these trials had no indicator to quantify biofuel production using WEF nexus approach. Thus, Moioli *et al.* (2018) studied and evaluated the efficiency of the crops presently used for biofuel production with respect to the WEF nexus. First-generation biofuels (biofuels obtained from agricultural food products) are a significant source of international biofuel supply (Rulli *et al.*, 2016). The production of biofuel has crucial societal implications (merits and demerits) that can be best understood whilst assessing the Water-Energy-Food nexus of biofuels. To establish the types of crops, the quantity required to produce bioethanol and biodiesel by some countries without specifying the mixture ratio with fossil fuel, Rulli *et al.* (2016), remodelled the design of biofuel consumption and trade with the help of data from various sources across the globe such as the FAO (2013), (USDA, 2021; RTFO, 2019; Swedish Energy Agency, 2015; Italian Ministry of Economic Development, 2015). The results found that on average, biodiesel consumes similar quantity of water resources as bioethanol, however it necessitates more land than bioethanol. As global production of bioethanol is greater than biodiesel, bioethanol impact on food security is greater with regards to the number of people who could be fed. The competition between food and biofuels should be emphasized as it is anticipated to become even more pronounced in the near future.

A study by Moioli *et al.* (2018) suggested a methodology for the WEF analysis, while considering all facets of the concept and summarising them in a single indicator. A major set-back of most of the available tools is that they do not address the issues as holistically as earlier stated. An assessment tool should be convenient to be used for making policies, whilst being comprehensive to thoroughly detail the current energy production under a

nexus perspective; there are few such tools currently available as suggested in several WEF nexus articles reviewed (Bazilian *et al.*, 2011; World Economic Forum, 2011; Hoff, 2011; Liu *et al.*, 2017; Keairns *et al.*, 2016). To design an index assessing the WEF nexus, a coherent understanding of the indicators serving as quantifiers (water, food, and land efficiency) underlining the single aspects of the nexus to produce biofuel is paramount. The index is adapted to calculate the quantity of resources needed to derive one unit of energy in terms of water, food, and energy. The maximum values reflect the global performance level to achieve high nexus index scores; to gain a full understanding of global nexus performance, it is important to communicate the farming techniques and index results for each crop in-depth. The high index scores signify that WEF resource management approaches are being implemented by some countries to produce biofuels.

As biofuels have been found to be a viable alternative to fulfil the energy needs internationally, there is need to develop an efficient scheme for the commercial production and logistic chain of biofuels. López-Díaz *et al.* (2017) aimed to optimize the production of biofuels with the help of the WEF nexus to meet regional biofuels demands using the material flow analysis technique to evaluate and account for the impacts of the production system with regards to arable land and water consumption. The resulting optimization framework was executed in Mexico to analyse the proposed framework's efficiency. The results were the quantity, values of required water, and the profit in the biorefining system.

To assess the sustainability of biofuels from WEF resources for biofuel production in Thailand is imperative as the government is activating a biofuel promotion policy. Agriculture, a key component of the nexus consumes about 70% of water withdrawals from water-holding bodies internationally (World Water Assessment Programme, 2009; Gheewala *et al.*, 2011). Silalertruksa & Gheewala (2019) also studied the sustainability of biofuel production using the life cycle assessment approach which aimed at understanding the relationship between land, water, and energy to produce food as well as generate biofuels. The assessment results showed that the bioethanol goal has a direct impact on future water shortage, land use change, trade-offs between food and fuel. For the purpose of maximizing the WEF nexus and its outputs, as this will foster sustainability, every resource sector of the WEF must perform optimally; thus, a study by Lovarelli *et al.* (2016) proposed key areas such as boosting land productivity, water productivity, and energy productivity. Some of these areas are crop productivity enhancement, and the use of suitable land for crop and these proposed areas are corroborated by Ngammuangtueng *et al.* (2019). With the aim of achieving sustainability, it is essential to draw needed resource in rightfully quantity, hence, the agricultural land resource should be accommodated into the WEF nexus as this would enable the robustness of the holistic nexus framework. Furthermore, studies that incorporate the "agricultural land" sector into the WEF nexus using both nexus index and LCA methodology are needed to evaluate the "agricultural land" sector's effect on the nexus.

Table 1
Types of nexus

<p>Environment: water-food (n=6)</p> <ul style="list-style-type: none"> • Evaluating crop production and water nexus • Enhancing the efficiency of consumption green water or the rainwater • Water consumption irrigation by shifting to low water. • Governance: • Advocating the design of extension and training events. 	<p>Environment: water-energy-food (n=28)</p> <ul style="list-style-type: none"> • Analysing the sugar for producing energy as alternative energy • Investigating the land and water requirements for producing bioethanol and biodiesel from crops such as sugarcane, soybeans, oil palm etc. • Irrigation reduction can reduce consumption of energy and greenhouse gases emission. • Governance: • Hydropower investment • Efficient irrigation system • Tools: integrated analytical model
<p>Environment: water-energy (n=3)</p> <ul style="list-style-type: none"> • Assessment of biofuel • Water pumping using solar pumps. • Treatment plant for wastewater • Stimulate well-operated treatment technologies. • Governance: • Improvement of accurate, fine-scale, site-specific data • Stakeholder engagement • Economic: Multiple market management approaches <ul style="list-style-type: none"> ○ -Products lifecycle evaluation ○ -Examining scenario of carbon and water prices 	<p>Environment: water-energy-land-climate (n=3)</p> <ul style="list-style-type: none"> • Mitigate susceptibility disaster resulting from climate change. • Assess water demand and water treatment. • Governance: • Addressing the challenges of GHG resulting from energy consumption. • Formulating frameworks that restores the climate as well as develop countries.

Table 2

Overview of crops, study goals, and methods used for assessing food crop systems as well as biofuels production

S/No.	Reference	Types of biofuel	Types of feedstock	Method / Model used	Scenario	Study goal(s)
1.	Rulli <i>et al.</i> (2016)	Bioethanol Biodiesel	Maize, rice, sugar beet Palm oil, soybean	Nexus Index	Netherlands	To assess the impacts of biofuels on food security.
2.	López-Díaz <i>et al.</i> (2017)	Bioethanol Biodiesel	Corn, Wheat, sorghum, sugarcane Jatropha	Material flow analysis	Mexico	To design and propose an optimization framework for the biofuel system utilizing and accounting for WEF nexus resource consumption.
3.	Silalertruksa & Gheewala (2018)	Bioethanol	Sugarcane	Life cycle assessment	Thailand	To assess and account for the sugarcane production systems effects (direct & indirect) on the land-energy-water nexus in terms of indicators.
4.	Silalertruksa & Gheewala (2019)	Bioethanol	Cassava, Sugarcane	Life cycle-based assessment	Thailand	To quantitatively assess the impacts of biofuel development on water, land, and energy.

3.2. Results of WEF nexus resource utilization for biofuels

To explore the WEF nexus for biofuels production and derive results, various methods, feedstocks, and biofuel types have been employed as shown in Table 2. The production of bioethanol on the world scale tripled from 17.1 billion litres in year 2000 to 49.5 billion litres in year 2007 (Statista, 2019). This trend shows that production scheme (WEF resource system) of biofuel crops for bioethanol are constantly improving especially in developed countries. Biodiesel production has also experienced growth, the total production in 2016 was approximately 24 billion litres (Statista, 2019).

This significant increment can be attributed to the proper implementation of resource nexus in developed countries as they are major producers of biofuels, whilst also not leaving out developing countries that have begun to incorporate the nexus approach, as seen in Silalertruksa & Gheewala (2019), López-Díaz *et al.* (2017), Rulli *et al.* (2016), and Moioli *et al.* (2018), to help resource management and assist policy making. These articles have employed varying quantitative approaches to minimize trade-offs while maximizing the desired outputs. One of the approaches used is material flow analysis which helps to develop an optimization framework to improve crop yield, increase biofuel production, and increase profit whilst using minimal resource. Material flow analysis details the metabolism occurring within the WEF nexus system by noting what quantity of resource goes into the system, what amount of output is achieved, generally assists in managing resources and tells how to improve the WEF system as well as maximize resource consumption in the future. Another similar approach implemented to harness the WEF nexus system for biofuel production, is the WEF nexus index. This approach utilizes a set of indicators to quantify WEF resource inputs into the biofuel production system as well as their productivity. The index helps to improve farming practices as well as minimize water and energy consumption. De

Laurentiis *et al.* (2016) also explained and gave evidence on how the LCA method was used to arrive at desired improvements in food production using the WEF nexus. Implementation of these approaches generates data that helps identify hotspots as well as less efficient indicators and decision are made to improve these. Thus, the WEF resources are judiciously managed to foster advancement of the biofuel production system as evident in regions where these WEF nexus practical approaches are being undertaken.

4. Discussion

The goal of this article is to give a thorough, extensive recap of the past and present relevant WEF nexus principles for developing biofuels. This is so because each of these biofuel classes possesses unique properties from raw materials to conversion procedures and techniques as well as their current state of technical development and diverse research & development setbacks. After reviewing these nexus research works retrospectively with a focus on the nexus methodology, keywords, and tools, it was found that several stakeholders all over the globe have carried out and implemented different researches with the nexus keyword but with diverse aims to be achieved. The reviewed papers revealed a total of 168 keywords among which, classified according to their importance to resources consumption and availability, were water scarcity, food security, bioenergy, climate change, biofuel, hydropower, wastewater treatment, and policy. As a result of this continuous awareness, many of the WEF nexus research works focused on production of biofuels, its feedstocks requirement (water and food consumption) as well as sustainability. Although the food, water, and energy sectors are inherently interconnected, the connection in terms of policy and implementation still needs more actions. Development of policies and approaches without regard for cross-sectoral

consequences, and poor sectoral coordination and institutional fragmentation, may cause resource conflicts and ultimately threaten the long-term sustainability of food, water, and energy security. An example of this approach is when extensive conceptual approaches are without any quantification and assessment tool to evaluate the nexus' interlinkages, resource use efficiency, and general sustainability. These extensive concepts are mainly drawn from conventional sectoral literature, e.g., productivity analysis based on engineering, commodity-logistics analyses, and agricultural soil-plant water assessments. It is worthy to state that, for all the complexities, context, and issues, the nexus approach might not give the desired results if an economic efficiency evaluation is not incorporated within the framework. Thus, it is important for nexus approaches to incorporate evaluation tools as this helps to identify and address hotspots, efficiency, and sustainability issues within their frameworks of WEF resource security and biofuels production. As noted earlier, with growing global awareness for the advancement of biofuels to substitute conventional hydrocarbon-based fuels, awareness is equally being raised concerning its sustainability issues with regards to increased production and consumption. An example to this effect is, biofuels sustainability criteria were clearly defined by the European Union in the European Renewable Energy Directive (European Union, 2009), and these criteria are now being included in regional laws. Environmental protection and mitigation of greenhouse gas are the focus of these criteria. To cater for the sustainability of water, regional guidelines, and supply-chain parameters for the optimal consumption of freshwater have been formulated through water footprint research (Hoekstra et al., 2011). A product's water use will fail the sustainability test if the production process or practice is in a location that is termed hotspot, a watershed where the total water resource available is inadequate during a particular period of the year. By considering the water sustainability requirements, the choice of source of energy might be impacted, and the prevailing energy alternatives being attained might also be impacted. Nevertheless, a holistic, coherent, and analytical methodology provided by the WEF nexus approach will improve the nexus-derived solution implementation in the context of coordinated governance, efficient resource-use, comprehensive decision-making, and sustainable results obtained via socio-political practicable schemes. After reviewing and thorough evaluation of the WEF nexus research in the literature, the importance of a holistic framework is evident. This is supported by results from Nilsson et al. (2012), Endo et al. (2017), and Rasul (2016) which all also noted that details of the interlinks of these WEF resources are limited; thus, reinforcing the calls of a decision-making framework, improved WEF resource database, integrated indices, and economic evaluation methods to assist policymaking. Hence it is imperative to work towards developing this nexus framework to share solution-driven common goals. Methods like nexus indices, models, and economic evaluation methods. These methods / framework should be disseminated to researchers, non-governmental organisations, and society stakeholders to formulate unified methods for merging single-sectored study findings as well as comprehending the dynamics of WEF

schemes to help mitigate deficiencies and foster integration of amongst the three resources sectors.

5. Conclusions

An extensive review analysis of the past and present state of the nexus analytical frameworks was provided for the nexus tools and methods for resolving the inherent complexities of a multi-sectoral relationships. This analysis reveals that to tackle composite challenges related to resource management, cross-disciplinary methods are essential to integrate environmental, socio-political facets of water, energy, and food; employ collaborative frameworks; and seek the engagement of decision-makers. This assessment also made it apparent that the nexus approach can be useful in formulating and developing of schemes and holistic policies that lays out pathways for thoroughly assessing transdisciplinary relationships and discovering areas of interactions. It is very likely that the resulting output of managing the WEF nexus resources holistically would be a sustainable WEF union characterised by maximum resource allocation, enhanced economic performance, and reduced environmental and health impacts; in other words, an ideal utilization of resources. The WEF nexus has been widely used internationally to solve resource management trade-offs to secure food, energy, and water and the results from this review show countries that can sustainably produce first-generation biofuels with the help of the nexus. Biofuels often spring-up discussions in several topics such as environmental impacts, energy accessibility, climate change, and overall sustainability. However, these discussions have not thoroughly given adequate thought to the water-energy-land-food nexus issues related to biofuels. Achieving these sustainable results from WEF nexus approaches would require evaluating the nexus effects on the well-being of the populace and the involvement of establishments / policies on management practices, especially at the community level. Hence, it is imperative to give emphasis to the formulation and development of a holistic nexus framework. More studies and research that incorporate the "agricultural land" sector into the WEF nexus using both nexus index and LCA methodology are needed to help strengthen and properly manage "land" as a resource.

6. Recommendations

After analysing the different approaches used by the reviewed nexus studies, it is necessary to lay emphasis on the continued use of the nexus system as it enhances sustainability, thus government and policymakers should ensure that policies and production schemes being practiced and executed fully give regard to the interconnectedness within the WEF resource systems as this will help strengthen the much-needed resource availability and use database. The government should also encourage investments into food and energy production schemes, as investments will provide the financial backing for the smooth running of the nexus system which will then translate to increased yield in food, water, energy with negligible environmental impacts. As earlier said in the concluding section, future research that incorporate the "agricultural land" sector into the WEF

nexus using both nexus index and LCA methodology are needed to help to properly manage “land” as a resource. The index and life cycle assessment methods are to be used to evaluate the sustainability of land use in terms of ecological footprint and land productivity for biofuel as well as food production. Thus, the results from these methods can potentially tell how much of the water, energy, land, and food resources are to be used which will not alter the ecosystem balance.

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Authorship confirmation statement

Abass A. Gazal and Professor Shabbir H. Gheewala conceived the biofuel WEF nexus review idea and presented the manuscript. Dr Thapat Silalertruksa and Dr Napat Jakrawatana assessed the manuscript and gave ideas on how improve it. Professor Shabbir H. Gheewala did the final checks and verification.

Author(s) disclosure statement(s)

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