A systematic approach for assessing water, energy and food security during the COVID-19 pandemic: case study of Mexico

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Abstract
Assessing the security of the water–energy–food nexus is a topic of great importance, which allows determining the situation of each resource to implement actions for sustainable management of these resources in today’s society. For this reason, a systematic procedure is proposed to evaluate the synergies of the water–energy–food nexus in a large region that is divided into subregions that allow considering their interactions. The new procedure considers the availability, accessibility and regional interdependence of resources while annexing economic and social aspects. A composite index called the WEF Global Index is developed, which involves the WEF nexus index and has nine indicators that evaluate the availability, accessibility and regional interdependence of each resource in the water–energy–food nexus. This new index considers the Gross Domestic Product per capita and the involved population. As a case study, the 32 states of Mexico were considered to assess the effects of the COVID-19 pandemic on the economy and the security of the water-energy-food nexus at the state level. For this, the composite index was evaluated in the years 2019 and 2020. The results show that from 2019 to 2020, the value of the global index increased in 13 states, in 21 states the security index of the WEF nexus increased, and in 9 states the GDP per capita index increased. On the other hand, the results indicate that in 11 states there was no improvement in the nexus security index due to the increase in water demand, which considerably affected the water availability indicator.

Keywords Water–energy–food nexus · Sustainability indicators · Scenario analysis · Sustainable development, security · COVID-19 pandemic

Abbreviations
IPIbpc Gross domestic product per capita index
IPob Population index
NR Northern Region of Mexico
SSR South Southeast Region of Mexico
WEF Water, energy and food nexus
WEF nexus index Water, energy and food nexus safety index

Parameters

$\varphi^i$ Weigh of the variables composing the WEF nexus index
$\sigma^i$ Weigh of the variables composing the Global WEF index

1 Introduction

Water, energy and food are three vital resources for human well-being, poverty reduction and sustainable development (FAO, 2014a). However, the rate of population growth, urban expansion, climate change (de Amorim et al., 2018) and industry-driven economic development have been critical factors that put pressure on available natural resources to meet the increasing demand for water, energy and food (Sarkodie et al., 2019). As the population increases and economic growth accelerates, it is projected that global water demand will increase by 55%, and energy and food production by 50% and 70%, respectively, by the year 2050 (UNEP, 2021).

The current situation and the numerous and complex relationships between food, energy and water resources make it urgent to solve these problems through holistic thinking since they contain multiple scales and components (FAO, 2014b). These relationships that exist from the initial stage of generation or extraction in each resource depend directly and indirectly throughout the supply chain on the remaining resources to operate machinery and promote different activities. For instance, energy requires water for its production, extraction and conversion. In turn, energy is used for the production of water and food, since electricity is necessary to drive the pumps that extract (from underground and surface sources), transport, distribute and collect water. Energy can be used in the form of fuel or electricity and less directly, in the production of fertilizers, where total greenhouse gas emissions will be significantly contributed. Food also requires water for its production, and some crops could be transformed into bioenergy.

As water, energy and food are totally interconnected, the development of approaches that address the position in the management and security of resources is crucial. On the other hand, the health crisis caused by the spread of COVID-19 is superimposed on other complex challenges that already exist, such as the fulfillment of the Sustainable Development Goals (SDGs), which range from the elimination of poverty to the fight against climate change, education, women’s equality, environmental protection and the design of our cities. In this context, it is of great importance to distinguish how these issues put stress on the functioning of fundamental services for health and human development, such as water, food and energy services. Therefore, the novelty of this work is the development of a methodology to measure the security of the water–energy–food nexus that, to the best of our knowledge, unlike the methodologies reported, considers simultaneously social and economic aspects. The set of indicators proposed in this work makes it possible to identify the impacts that the COVID-19 pandemic had on the water, energy and food sectors in order to intervene in the most vulnerable sectors and reduce such impacts. In addition, through this methodology, the sectors can be analyzed to create more resilient systems, improving the ability to respond and adapt to any future situation whether climatic and/or health in the best possible way, with the above could also improve decision-making for future pandemics or any other event. This methodology could also be applied in scenario analysis, risk
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analysis and simulation of WEF systems. These approaches are increasingly appreciated as tools to structure complex policy questions (Scoblic & Tetlock, 2020) and as a useful approach for FEW resilience planning (Calder et al., 2021).

In this work, Mexico was chosen as case study because it is a country with many natural resources, renewable resources such as water, solar radiation, tides of the two oceans and wind; non-renewable resources such as hydrocarbons, metals and minerals, which are exploited and are essential for its economy. Therefore, the situation of the states of Mexico was evaluated in terms of WEF nexus security during the COVID-19 pandemic in a quantitative way through the elaboration of a composite indicator called WEF global index. In the framework of the WEF nexus security, 9 variables are analyzed that take into consideration the basic components of security in the three resources which are availability, accessibility and regional interdependence, besides including indicators of GDP per capita and population, with this quantification adapted to reality and based on the available information we can know the environmental, economic and social advances or setbacks in the area under study during the COVID-19 pandemic since this situation increases the tension in the functioning of the WEF systems. One of the main advantages of the WEF Global index is that it can be a first step in building resilience to avoid catastrophic risks in future viral pandemics or climatic events and thus improve the ability to ensure water, energy and food services in highly complex contexts, in addition to being a tool to help decision-makers, whether they are analysts or governmental, social and/or economic planners, to make better decisions.

In the following subsection, a literature review is presented, in which the sustainable development goals proposed by the United Nations that are directly and indirectly linked to the water–energy–food nexus are presented. It also discusses methodologies that have been used to assess the security of the WEF nexus over time and at different scales or case studies. Moreover, this section highlights methodologies that have been proposed that include indices to assess the security of a single resource or the combination of two of them. Finally, the subsection on the water–energy–food nexus and COVID-19 mentions the negative impacts on the environment and the economy during the COVID-19 pandemic.

2 Literature review

2.1 Water–energy–food nexus

In 2015, the United Nations General Assembly adopted The 2030 Agenda for Sustainable Development comprising 17 Sustainable Development Goals (SDGs) and 169 targets whose general purpose is to bring about the creation of a more equitable, fair, peaceful and prosperous global society by balancing the three inseparable dimensions of sustainable development: the economy, society and the environment. Energy, water and food systems are key elements within SDGs 2 (zero hunger), 6 (clean water and sanitation) and 7 (clean and affordable energy), as they are closely related to the complex linkages of the WEF systems (Bieber et al., 2018). In addition, they also indirectly affect SDGs 11 (sustainable cities and communities), 12 (responsible production and consumption) and 13 (climate action) through SDGs 2, 6 and 7. Therefore, it is imperative to quantify the WEF nexus and confirm its global relevance (UN, 2018).

Consequently, interest in the WEF Nexus from different sectors has grown on a worldwide scale. Recent literature has identified the main challenges and outlined the future
objectives of the nexus. The WEF nexus approach has been investigated to assess the feasibility and sustainability of projects (Endo et al., 2017), the role of investment, governance and institutional policy (Kurian, 2017; Wichelns, 2017). In addition, estimation methods used so far include econometric analysis (Rasul, 2016), life cycle analysis (Dantas & Soares, 2022; Garcia & You, 2016), input–output models (Heard et al., 2017; White et al., 2018), computational general equilibrium modeling (Afshar et al., 2021), agent-based modeling, integrated index modeling (Bijl et al., 2018), system dynamics modeling, physics-based modeling, mathematical and statistical analysis, and ecological network modeling (Zhang et al., 2018a).

One of the most relevant research areas on the WEF nexus is the development of indices where the security of resources has been investigated in terms of availability, accessibility and quality; that is, their level of sanitation and impact on human health. Generally, they have focused on the development of specific indicators for each sector. For example, for water systems, there are the Water Availability Index (Molle and Mollinga 2003), the Water Scarcity Index (Brown, 2011), the Water Resources Vulnerability Index (IDEAM, 2010), the Social Water Stress Index (Juwana et al., 2010), the Water Stress Indicator (WSI) and the Water Poverty Index (WPI) (El-Gafy, 2018). Some researchers have emphasized water conservation methods in modern agriculture at different scales from orchards (Fernández et al., 2020) to the national level (Zhang et al., 2018b) or applied to agricultural residues (Garcia & You, 2017). The set of indicators is used to monitor water resources as part of target 6.4 of the SDGs (Vanham et al., 2018). And focusing on water quality, Hernandez-Cordero et al. (2020) developed an integrated indicator of multimetric evaluation that contains indices of concentration of dissolved gases, indicators of clarity and underwater grasses.

To measure energy security, Sovacool and Mukherjee (2011) summarized energy security indicators in a wide range of dimensions, dealing with availability, price and affordability of energy, technological development and efficiency of use, in addition to some normative and regulatory metrics. Löschel et al. (2010) addressed the accessibility component of energy security, focusing on the energy supply process dealing with the behavior of energy prices and the future performance of the energy system considering the economic and political stability of the market. Ren and Sovacool (2014) investigated the cause-and-effect relationship between numerous energy metrics and stated that availability and affordability have the strongest influence on national energy strategies. Matchamadol and Kumar (2013, 2014) introduced the Aggregate Energy Security Performance Indicator (AESPI) to improve the electricity sector in Phuket.

Considering food security, Gil et al. (2019) proposed a set of metrics using indicators, including availability, access, utilization, and stability, and, unlike current SDG indicators, these metrics provide an implementation of more fluid and practical policies which focus solely on food availability. Namany et al. (2019) used food self-sufficiency as an indicator to assess food security in Qatar and improve the level of national food production. Alternatively, Ritzema et al. (2019) adopted the Household Dietary Diversity Score (HDDS) to quantify food utilization in the Mekong subregion.

However, there is needed an index that considers all three resources: water, energy and food, instead of just one which concentrates on a single sector like the previous indices, to evaluate the performance of the three sectors and their interrelationships as these tools are essential in the understanding of the nexus concept and to determine areas for improvement, especially in developing countries.

In this sense, Saladini et al. (2018) proposed an indicator-based tool to assess the SDG targets in the context of the WEFE nexus in the Mediterranean region. El-Gafy (2017)
suggested indicators considering water and energy consumption, mass productivity and economic productivity based on a water–food–energy nexus index (WFENI) to analyze Egyptian crop production. Hua et al. (2020) identified priority biophysical indicators to promote the WEF nexus within planetary boundaries based on global datasets of official SDG statistics. Yuan and Lo (2020) developed the "Linked Indicators for WEF Availability" (LIFEWAY), which is a composite index that measures a country’s sustainability achievement. Mahlknecht et al. (2020) proposed a WEF index to assess the progress of water, energy and food security at the national level in the Latin American and Caribbean region. Cansino-Loeza et al. (2020) used a systematic approach to assess the WEF nexus in the context of sustainable development considering the availability, accessibility and sustainability of WEF resources in resource-scarce regions, and Sánchez-Zarco et al. (2020) extended this approach to semi-arid climates in Mexico.

The COVID-19 pandemic has shown us that the interactions between WEF systems, viral pandemics, and human health have not been extensively studied as there is practically no quantitative analysis of any of these compensations or feedbacks (Calder et al., 2021). However, it is also revealed that WEF interconnections are not only vulnerable to resource constraints, but also to disruptions in human and financial capital on the supply and demand side (Al-Saidi & Hussein, 2021). Since attempts to stop the spread of the virus have resulted in widespread economic and social disruption. Supply-side shocks have been characterized as having to do with the disruption of labor inputs and mismatches in the size of food packages caused by the closure of restaurants and other food services (Calder et al., 2021); however, we also consider disruptions in the logistics of products, which can be internal (displacement of producers and intermediaries, interruptions in national roads) or external, which can disrupt international trade supply chains through border road blockades or closures of ports and airports, as well as delays in customs. In addition, the volatility of internal prices and external policies that restrict exports, which can be tariff or sanitary, are considered. On the other hand, the risks on the demand side have to do with interruptions in access to products, reduced purchasing power, economic decline, unemployment, and increased poverty and inequality (FAO & ECLAC, 2020).

It is important to highlight that those previous methodologies have tried to find indices and methodologies that allow evaluating the synergies that exist between the three resources; however, none of them has considered the implication of the indices that measure the security of the water–energy–food nexus simultaneously with human development by including economic and demographic indicators of the region under study.

2.2 The water–energy–food nexus and COVID-19

The WEF problems have been amplified directly and indirectly by the COVID-19 pandemic that began as a health emergency and has triggered an unprecedented socioeconomic crisis, stalling progress on the SDGs (UN, 2015) related to the WEF nexus. The COVID-19 pandemic pushed 100 million people into poverty, doubling the number of hungry populations by 2020 (Nature, 2021). It also led to the worst recession since World War II, threatening WEF’s global security (Blake & Wadhwa, 2020). Global food prices have increased by 38% since January 2020 due to the high demand caused by COVID-19 in the supply chain (Baffes & Wu, 2021). Due to the strong demand for sanitation and clean water to prevent virus transmission, water-scarce regions came under additional pressure. In contrast, global energy demand in 2020 decreased by an average of 5% as transportation, trade and production declined (IEA, 2020). The excess supply caused the collapse of
the oil market with the reference price in April 2020 (Eroğlu, 2021). A well-functioning international market is essential to regulate supply and demand. However, the confinement imposed restrictions and limitations on international trade, disrupting the supply chain. The economic recession, coupled with a sharp drop in national GDP and rising unemployment, weakened the demand for WEF resources.

Developed countries were more vulnerable to supply-side risks due to their high dependence on international supply chains. Developing countries were more vulnerable to demand-side risks due to higher retail prices and income shocks during the pandemic, in addition to inadequate WEF supplies (WHO, 2020). The COVID-19 pandemic has wreaked havoc everywhere and especially attacked the weaker points of societies, taking advantage of and aggravating the innumerable inequalities in human development (UNDP, 2020).

The COVID-19 pandemic highlighted how human activities have a direct impact on the environment and human development. Environmental benefits have been observed due to the blocking of activities; however, they do not meet the criteria of sustainable development, since this has been at the cost of reduced industrial production and economic development. Therefore, it is necessary to resume economic activities, but with an integrated approach to the management of water, energy and food resources. If done correctly, they have the potential to guarantee the sustainability of the environmental benefits achieved during COVID-19 pandemic.

In this context, the nexus approach emerges as a response to the challenges of achieving water, energy and food security in the face of growing pressure and competitiveness on natural resources (Bazilian, et al., 2011; Biggs et al., 2015). The WEF nexus approach allows for more integrated and effective policymaking, planning, monitoring and evaluation concerning the different sectors of the nexus (Giampietro et al., 2013). The WEF nexus as a conceptual framework can help reduce unexpected sectoral trade-offs and promote sustainable development in WEF systems as it is important for the regular operation and future development of cities (Martin & Grossmann, 2015; Zhang et al., 2018a).

It is intended to evaluate the security of the WEF nexus and link it with social and economic aspects in Mexico since it has performed below expectations in terms of growth, inclusion and poverty reduction compared to similar countries in addition to those inequalities that remain high (World Bank, 2021). Mexico ranks among the top 25% of nations with the greatest social inequity in the world according to data from the Oxford Committee for Famine Relief (OXFAM) (Esquivel, 2015). Extreme inequality is observed when verifying that in 2020 in Mexico more than 44.9 million people were living below the poverty line (43.9% of the population), of which 10.8 million live in extreme poverty (CONEVAL, 2020).

### 3 Problem statement

The sustainable management of the water–energy–food nexus is key for achieving the Sustainable Development Goals (SDGs); however, the progress of many countries to achieve these goals is still lagging since most countries face resource constraints and serious social and environmental problems. These problems have been amplified directly and indirectly by the COVID-19 pandemic, which has threatened the water–energy–food nexus security. In the food sector, as the food demand increases, global food prices also increase. In the water sector, water-scarce regions come under
additional pressure due to the strong demand for sanitation and clean water to prevent virus transmission. In the energy sector, the global energy demand decreases as transportation, trade and production decline. In addition, the COVID-19 pandemic pushed 100 million people into poverty and raised the unemployment percentages. Considering this, a methodology to quantify the security of the water, energy and food sectors that considers economic and social aspects in a particular region should be developed for effective policymaking, planning, monitoring and evaluation of the WEF nexus during the COVID-19 pandemic. Therefore, a composite index called Global WEF Index is proposed to evaluate the security of the WEF nexus and its sectors through accessibility, availability and sustainability indicators as well as indicators related to the GDP and population of a region. With the evaluation of the Global WEF Index, the status and progress of the WEF nexus and its sectors could be studied to take corrective actions and for the improvement of the SDGs.

4  Global WEF index methodology

The Global WEF index is a composite indicator, which means that it is formed by different individual indicators related to the water, energy and food sectors. The construction of a composite index according to Nardò et al. (2005) is presented in Fig. 1.

4.1 Development of a conceptual framework

The reference framework used aims to assess the security of the water, energy and food nexus, considering the interrelationships between the sectors in a systemic scheme, where economic and social aspects are also included to generate an integrated index.

![Fig. 1 Methodology for the construction of the Global WEF Index](image-url)
4.2 Selection of indicators

To establish the indicators to evaluate the WEF nexus security, the following steps were followed:

1. Selection of the unit of analysis, which is the main entity being analyzed in a study. For instance, in this work, a country addressed by states was selected as a case study.
2. Define the indicators that will make it possible to quantify the security of the water, energy and food sectors and the security of the WEF nexus.
3. Select the variables of each indicator (Fig. 2).
4. Find the data needed to calculate each variable (Tables 1 and 2).
5. Document each variable according to its characteristics.

Table 1 shows that water availability was obtained from water generated from groundwater (CONAGUA, 2021a) and surface water (CONAGUA, 2021c) minus water consumption in agriculture, industry, electricity generation and public supply (CONAGUA, 2021b). Accessibility takes into account the population with piped water services at home (SEMARNAT, 2020b). For regional interdependence, it is the water consumed minus the imported water needed to meet demand. In the energy sector, availability is obtained from the difference between electricity generation and consumption (SENER, 2021b). Accessibility takes into account the population with electricity services in the household (SEMARNAT, 2020a). Energy regional interdependence evaluates the energy produced through renewable sources compared to the total energy footprint (SENER, 2021a).

In the food sector, availability was calculated by the subtraction of food servings produced and minimum servings required, assuming 3 servings of vegetables, 2 of fruit, 6 of cereals, 1 of dairy, 2 of dried legumes and 2 of animal foods, each serving of 100 g except dairy which is 240 g. Accessibility considers the existing healthy population obtained from the total population and the undernourished population (CONEVAL, 2020). Regional Interdependence considers the total food production from agricultural, livestock and fishery production minus the amount of imported food (SIAP, 2021b). In the regional interdependence term, we are measuring the capacity of the state to provide water, energy and food to all localities, both rural and urban, and to the various sectors within its territory. With this variable, it can be observed that when the value is equal or close to one, the state is capable of supplying itself without depending on others.

4.3 Imputation of missing data

The absence of data is common when the WEF nexus security is evaluated. In this work, for the addressed case study, some states present a lack of data at certain time intervals. However, to deal with missing data, a simple imputation of the data could be made, replacing the missing information with existing records.

The missing data of the case study presented were the accessibility of water and energy for the year 2019. In Mexico, population and housing censuses are made every 10 years. Therefore, the water and energy accessibility data available correspond to the years 2010 and 2020 which were the data used to quantify the accessibility indicator. On the other hand, in the case of data associated with food accessibility, the data corresponding to the year 2018 were used, which were the data available immediately prior to 2020.
4.4 Data normalization

The variables of the WEF nexus index are estimated using rates or percentages of
variation, which results in a dimensionless indicator (Table 3). To normalize the GDP per capita and population variables, the method of distance to a reference unit of analysis (in this work, it refers to the states of a country) was used (Table 4). The change assumes that all variables can be compared since their unit of measurement becomes a
value in the interval $[0,1]$. The highest performing unit of analysis is equal to 1, and the lowest is equal to 0.

### 4.5 Weighting of normalized information

Equi-proportional weights were applied to quantify the WEF nexus index, that is, identical weights that assign the same priority to all variables. For the Global WEF index, the same weight was also applied to each indicator. The assigned weights are summarized in Table 5.

The weights considered in each of the indicators can be modified by decision-makers, according to the specific location, constraints and requirements of each region or case study where it is to be applied. The assignment of weights should be a collegial decision among all decision-makers associated with a case study, such as governmental, social and industrial analysts and/or planners as an alternative for the efficient management of resources that could bring economic, social and environmental benefits.

### 4.6 Aggregation methods

Considering that the superscript $i, 1 \leq i \leq p$ represents the variables involved and $j, 1 \leq j \leq N_{states}$ represents the units of analysis (in this case the states of a country) of the sample, $\gamma_j^i$ is the weight of the variables that compose the WEF nexus index. The information of used aggregation techniques is detailed below.
The aggregation of the variables is done at two levels as shown in Table 6. In the first level, the arithmetic mean of the variables is calculated, which results in the WEF nexus index, obtaining this value for each state and year studied. With this form of aggregation, if one variable is very high and another is very low, they offset each other and result in an average score. The first aggregation of variables is done with the following relationship:

\[ I_t^j = \sum_{i=1}^{p} \varphi^i \cdot y_{it} \forall t, j \in J \]  \hspace{1cm} (21)

With

\[ \sum_{i=1}^{p} \varphi^i = 1 \]  \hspace{1cm} (22)

\[ 0 \leq \varphi^i \leq 1 \forall 1 \leq i \leq p, \forall j, 1 \leq j \leq N_{\text{states}}. \]

where \( t \) is the year of study.

The arithmetic mean formula for the WEF nexus index was developed as shown below:

\[
\text{WEF nexus index}_t^j = \left( \frac{1}{9} \times W_{1,t}^j \right) + \left( \frac{1}{9} \times W_{2,t}^j \right) + \left( \frac{1}{9} \times W_{3,t}^j \right) + \left( \frac{1}{9} \times E_{1,t}^j \right) + \left( \frac{1}{9} \times E_{2,t}^j \right) + \left( \frac{1}{9} \times E_{3,t}^j \right) + \left( \frac{1}{9} \times F_{1,t}^j \right) + \left( \frac{1}{9} \times F_{2,t}^j \right) + \left( \frac{1}{9} \times F_{3,t}^j \right) \forall t, j \in J
\]  \hspace{1cm} (23)

At the second level, the aggregation gives rise to the Global WEF Index using the geometric mean so that some areas are not offset against others. \( \omega^i \) is the weight of the variables that compose the Global WEF index. The second aggregation is calculated as follows:

\[ I_t^j = \prod_{i=1}^{p} (y_{it}^{ij})^{\omega^i} \forall t, j \in J \]  \hspace{1cm} (24)

With

\[ \sum_{i=1}^{p} \omega^i = 1 \]  \hspace{1cm} (25)

\[ 0 \leq \omega^i \leq 1, \forall j, 1 \leq j \leq N_{\text{states}} \]

where \( t \) is the year of study.

The relationship developed for the calculation of the Global WEF index is stated as follows:

\[
\text{Global index}_t^j = (\text{WEF nexus index}_t^j)^{\frac{1}{3}} \times (\text{IPIBpc}_t^j)^{\frac{1}{3}} \times (\text{IPob}_t^j)^{\frac{1}{3}} \forall t, j \in J
\]  \hspace{1cm} (26)

### 4.7 Percentage variation measurement

For the calculation of the percentage of variation, the linear approach represented in Eq. (27) was used:
where \( V_1 \) represents the value of the present index, and \( V_0 \) represents the value of the past index.

\[
\% \Delta = \frac{V_1 - V_0}{V_0} \times 100\% \tag{27}
\]

5 Case study

It is proposed to use the national situation of Mexico as a case study, dividing the country into its 32 states, to demonstrate the usefulness of the new WEF Global Index that evaluates the security of the water–energy–food nexus and considers economic and social aspects.

Of the water in the form of precipitation that Mexico receives, it is estimated that 72.1% is evapotranspired and returns to the atmosphere, 21.4% runs off through rivers or streams, and the remaining 6.4% infiltrates the subsoil naturally and recharges aquifers, taking into account outflows (exports equal to 432 \( \text{hm}^3 \)) and inflows (imports equivalent to 48,381 \( \text{hm}^3 \)) of water with neighboring countries (CONAGUA, 2018).

Of the total water extracted, the largest volume is used by hydroelectric power plants, which generate about 12% of the country’s electricity. However, the use of hydroelectricity does not imply the consumption of the resource, since the water used generally returns to bodies of water without damaging its quality. Even so, since large volumes of water are reserved for hydroelectric plants, they cannot be used for other purposes.

In terms of consumptive uses, approximately 61% of water comes from surface sources (rivers, streams, and lakes), while the remaining 39% is extracted from underground sources (aquifers). The agricultural sector uses 76% of extractions, 14% is extracted for public supply, while 5% corresponds to what is used by self-supplied industry and 5% is used in thermoelectric plants (CONAGUA, 2021b).

For the Mexican electricity sector in 2020, the installed capacity of Clean Energy Power Plants such as hydroelectric, geothermal, wind, photovoltaic and bioenergy represents 30.8%, equivalent to 25,594 \( \text{MW} \) (SENER, 2021a).

Mexico is recognized as the 12th food producer among 194 nations. This sector employs more than six million people. 1.9 million tonnes were fished, and 7.4 million tonnes of meat were generated for a total volume of agricultural and fishery production of 290.7 million tonnes (1.04% more than in 2019). The value of food production reached US$60 billion, which was 3.4% higher than in 2019 (SIAP, 2021a).

In macromeconomic terms, Mexico is the fifteenth world economy and thirteenth by purchasing power parity (PPP); on a regional scale, it is the second economy in Latin America and the fourth in the continent (IMF, 2021). In 2020, tertiary activities (tourism, commerce and services) represented 64% of Mexico’s GDP, followed by secondary activities (which include mining, manufacturing, construction and generation, transmission and distribution of electricity and gas supply) with 32% and primary activities (such as agriculture, forestry, livestock, fishing and aquaculture) with 4% (INEGI, 2020a). Some general data can be seen in Table 7 and specific data in the Supplementary Information section.
6 Results

The Global WEF index of Mexico and its states were quantified to evaluate the progress of the water, energy and food security and the impact on the SDGs during the COVID-19 pandemic. To quantify the indicators of the Global WEF index for the case study of Mexico, information from official Mexican government websites was used. Data related to the water sector were obtained from the National Water Information System (SINA) and the National Water Commission (CONAGUA); energy sector data were obtained from the Energy Information System (SIE) and the Secretary of Energy (SENER); and food data from the Agrifood Information System for Consultation (SIACON NG) of the Agrifood and Fishery Information Service (SIAP). GDP per capita and population data per state were obtained from the National Institute of Statistics and Geography (INEGI).

The results of the 9 evaluated variables of the WEF Nexus Index are shown in Fig. 3 for the 32 states in 2019 and 2020, respectively. The WEF Nexus Index ranges between 0 and 1, with 1 being high performance and 0 being low. The four states with the highest WEF nexus security are Chiapas, Oaxaca, Nayarit and Michoacan in 2019 and 2020. Chiapas ranks the highest. It is the state with the highest availability of water in the country. Oaxaca is the fourth state with the highest water availability. Nayarit is in third place, and it is the fifth state with the largest amount of water available in the country. And Michoacan ranks fourth, and it is ranked seventh in the evaluation of the variable $W_1$ of water availability in 2019 and eighth place in 2020. Regarding the energy regional interdependence variable $E_3$, the states present scores of 1 in both years since the electricity generated from renewable sources is greater than their electricity consumption. In the case of Chiapas and Oaxaca, electricity is produced from hydro energy, wind energy and bioenergy, and Nayarit generates electricity from hydro energy, geothermal energy and bioenergy, and Michoacan from hydro and geothermal energy (SENER, 2018).

As can be seen in Fig. 3, Chiapas and Oaxaca have high availability and regional interdependence indices of water, energy and food; however, a small percentage of the population has access to water, electricity and quality, nutritious food, since they lack basic services in their homes. On the contrary, Mexico City has high scores for accessibility to WEF nexus resources but does not have availability of resources and therefore low regional interdependence indices are presented.

The four states with the lowest WEF nexus security are Morelos, Estado de Mexico, Quintana Roo and Mexico City. The states of Morelos and the State of Mexico have low values in 7 variables. They have a low score in the energy regional interdependence

| Table 7 | Data from Mexico |
|----------------|-----------------|
| Surface area of Mexican territory | 1,964,375 km² |
| Population in 2020 | 126,014,024 |
| Water received in the form of annual precipitation | 1,449,471 hm³ |
| Annual renewable freshwater | 451,585 hm³ |
| Installed capacity | 83,121 MW |
| Area used for agriculture | 24.6 million hectares |
| Area used for livestock | 109.8 million hectares |
| Coastal area for fishing | 11 thousand kilometers |
| Nominal Gross Domestic Product | 1,074 billion USD |
variable, which means a low amount of electricity from renewable sources is produced, while for variables $W_1$ and $E_1$, a score of 0 represents the unavailability of water and energy in both years, despite the decrease in electricity consumption that dropped from 17,489,405 GWh in 2019 to 15,980.43 GWh by 2020 (SENER, 2021b). However, the results of $W_1$ and $E_1$ indicate that the demand for resources is much greater than local production. In the state of Quintana Roo, there are values in 7 variables for both years, the energy availability $E_1$ has a score of 0 since its electricity generation is equivalent to around 3% of its electricity consumption. The highest percentage of energy generation comes from turbogas and internal combustion plants (SENER, 2018); therefore, the energy regional interdependence $E_3$ presents values very close to zero. The food regional interdependence $F_3$ in these states is also very low because food production was 256,504.09 and 310,760.73 tonnes and milk production was 4,677 and 5,453 thousand liters for the years 2019 and 2020, respectively, these being the lowest indices of $E_3$ in the whole country (SIAP, 2021b).

Fig. 3 Ranking of States of Mexico according to their score in the WEF Nexus Index in a 2019 and b 2020
The worst score in the evaluation of the WEF nexus index corresponds to Mexico City with 0.466 and 0.464 for the years 2019 and 2020, because it only has values in 5 variables and the remaining 4 have scores of 0 (W₁, E₁, E₃, F₃). Water availability (W₁) is equal to 0 because the city shows a water deficit; 512.8 hm³ of water is generated and 603.8 hm³ is concessioned (CONAGUA, 2021b). Energy availability (E₁) and regional interdependence (E₃) present low indicators since electricity generation (985 GWh) from fossil fuels in turbogas, internal combustion, efficient cogeneration and conventional thermoelectric power plants, represents around 8% of electricity consumption (SENER, 2018). In addition, from 2019 to 2020 electricity consumption had a decrease from 12,910.523 GWh to 11,354.75 GWh (SENER, 2021b). And finally, food regional interdependence (F₃) is equal to 0 because food production was 386,241.96 and 379,432.24 tonnes, and 12,402 and 12,180 thousand liters of milk production in 2019 and 2020, respectively (SIAP, 2021b), being the second-lowest place in the whole country with food regional interdependence which causes a large amount of food to be imported to supply the second largest population in the country (9,209,944 inhabitants) (INEGI, 2020b).

Figure 4 shows the results of the variables water availability (W₁) and water accessibility (W₂) of the states. To calculate W₂, data from 2010 and 2020 were used (SEMARNAT, 2020b), which shows an improvement in the percentage of the population with access to piped water. In both years, the states with the highest water availability, such as Chiapas, Tabasco and Oaxaca, are states where the population has low access to piped drinking water services at home. In a critical case are the states of Veracruz and Guerrero, as they
have low availability and accessibility to the vital liquid in the country. Veracruz generated 4,407.15 hm$^3$ and 4,304.5 hm$^3$ of water in 2019 and 2020, respectively; however, it has a concessioned volume of 6,029.27 hm$^3$ of which 64.2% is for agricultural use, which is why it is in water deficit. Guerrero is also in this situation because it had a water volume of 3,655.12 hm$^3$ in 2019 and 3,199.64 hm$^3$ in 2020, but it had 4,505.98 hm$^3$ of concessioned water (CONAGUA, 2021b) of which 69.3% is for use in the Plutarco Elias Calles Thermoelectric Power Plant, which is the largest in the country with a gross generation of 18,081 GWh (SENER, 2021a).

In the energy sector (Fig. 5), a slight improvement in energy availability ($E_1$) is seen in 2020 compared to 2019, because national electricity consumption decreased from 218,929.62 GWh in 2019 to 206,564.08 GWh in 2020 (SENER, 2021b); this decrease was derived from the strategies to contain the spread of COVID-19, among which the closure of non-essential activities such as shops and industries not considered essential, caused some sectors to be affected, as are the cases of the Commercial sector ($-10.8\%$), Medium Company ($-8.1\%$) and Large Industry ($-5.6\%$). In contrast, the Residential and Agricultural sectors grew 6.4% and 10.8%, respectively (SENER, 2021a). In addition, the figures show peaks of score 1 in variable $E_3$ corresponding to the states that generate a large part of the electricity from renewable sources already mentioned above.

In the food sector (Fig. 6), the situation improves compared to the water and energy scenarios since most of the states have high food availability and regional interdependence except for Quintana Roo and Mexico City which show $F_3$ values equal to zero. For

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**Fig. 5** Behavior of variables $E_1$ electricity availability, $E_2$ electricity accessibility and $E_3$ energy regional interdependence in (a) 2019 and (b) 2020 in each state.
the year 2018 to 2020, Tabasco improved its food accessibility; however, it is still the state with the lowest access to nutritious and quality food in the country.

Figure 7 shows the results obtained from the WEF nexus index of the Mexican states, using red for low values, yellow for average values and green for high values. The small map has a scale from 0 to 1, and the large map has a scale of the minimum and maximum value obtained from the evaluation of the states to visually identify the best and worst evaluated states.

In the case of the water sector, 46.8% of the states had a decrease in availability, and in the case of regional interdependence, 28.1% of the states showed a decrease by 2020. Regarding water accessibility, Tlaxcala was the only state that decreased in this variable, while Chiapas, Tabasco, Oaxaca and Guerrero had an improvement from 2010 to 2020. This was caused in part by the effects of climate change in Mexico, since in 2020, for the second consecutive year, the total annual rainfall was below average, from the north to the center of the country. This low precipitation was accentuated mainly in the northwest and the coastal states of the Mexican Pacific, except for the coast of Jalisco and Colima. In the case of temperature, an increasing trend has been observed since 2004; an anomaly of 1.4 °C above the climatological average was recorded in 2019 and 2020, making them the warmest years since 1953 (CONAGUA, 2020a). This puts pressure on natural resources, the economy and the population in several regions of the country.
In the energy sector, 43.7% of the states improved their energy availability and 59.3% in the case of energy regional interdependence from 2019 to 2020. This improvement was caused by the decrease in electricity consumption due to the sanitary contingency originated by COVID-19, which caused the suspension of productive activities throughout the country. Regarding energy accessibility, the only state that showed a decrease was Tlaxcala, while Oaxaca and Guerrero were the states with the highest percentage of improvement from 2010 to 2020.

In the food sector, 56.2% of the states show a decrease in the food availability variable, the worst being the state of Mexico, Queretaro and Mexico City. Nuevo Leon ranks the lowest with -5.7%. However, 81.2% of the states have a high score that is equal to or greater than 0.9. In the case of food accessibility, 53.1% of the states had a decrease, being Tlaxcala and Quintana Roo the worst and Tabasco having the highest increase in food accessibility in its population. In addition to this, 90.6% of the states in 2018 and 84.3% in 2020 had a score equal to or greater than 0.7. With regard to food regional interdependence,
81.2% of the states had an improvement from 2019 to 2020, being the state of Mexico and Nuevo Leon the most improved states, while 4 states Sinaloa, Baja California, Chihuahua and Tamaulipas had a slight decrease between 0.01 and 1.72%. This is derived from a decrease in food production in 2020. A score equal to or greater than 0.71 was obtained in 84.3% of the states. Being the primary sector in the country the only one that registered a positive growth compared to the rest of the economic activities, which allowed to eliminate any possibility of scarcity and thus maintain the food supply to the population in confinement.

Due to the surely lasting effects of the COVID-19 pandemic on the economy, nutrition and health of families and the most vulnerable children, the participation and contribution of all sectors of society are required, led by the federal government, with the participation of international and civil society organizations, health professionals, the media and society in general to implement urgent measures to mitigate such impact. Considering actions that encompass all the dimensions that interact as part of the agrifood system, and that consider all the links in the supply chain of inputs and food. For example, maintaining access to food with special attention to vulnerable populations (i.e., children, women, indigenous populations), reducing food losses, ensuring national food production, keeping food and input supply chains operational, promoting the consumption of vegetables, fruits and legumes, as well as the consumption of drinking water and facilitating access (in terms of price and proximity), especially for the low-income population or those whose income, have been severely affected (UNICEF, 2020). For citizens, it is considered convenient to plan food purchases so as not to overdo it and acquire unnecessary products.

For both years, the State of Mexico, Quintana Roo and Mexico City are observed in red color, which shows the lowest values of the WEF nexus index in the entire country; however, 65.6% of the country’s states for 2020 had a slight improvement in the security of the WEF nexus, being the state of Tabasco the one with the highest percentage of increase in the value of the WEF nexus index with 3.9%. The remaining 34.4%, which represents 11 states, had a decrease in the value of the WEF nexus index, the worst being the state of Chihuahua with − 2.9% (Fig. 8a).

Figures 8b and 9 show the rankings of the IPIBpc and IPob indices in order from highest to lowest. Campeche ranks first in the IPIBpc index with a score of 1 because it has the highest GDP per capita in the country with 25,671 USD (INEGI, 2019), although its GDP is not one of the highest in the country since it occupies the 13th position. It is one of the entities with the smallest population occupying the 30th position with 928,363 inhabitants (INEGI, 2020b), which is demonstrated in the IPob Index Ranking, while the value of 1 for the IPob index is for the State of Mexico with the largest population in the country with 16,992,418 inhabitants in the year 2020 (INEGI, 2020b).

Figure 10a shows that 25% of the states had an improvement in the IPIBpc index. From 2019 to 2020, the states with the largest decrease in the GDP per capita Index were Quintana Roo and Baja California Sur as they had significant reductions in income from secondary and tertiary activities. Tabasco had the largest increase in the GDP per capita index due to its secondary activities. At the national level, the Mexican economy declined by 8.5% in 2020, with a sharp drop in the first half of the year, due to the supply and demand shocks derived from the COVID-19 pandemic, which had a profound impact on companies, employment and households, as evidenced by the 10.2% drop in secondary activities (which include mining, manufacturing, construction and generation, transmission and distribution of electric power and gas supply) compared to the previous year. Tertiary activities (such as tourism, commerce and services) recorded an annual drop of 7.9% and only primary activities (related to agriculture, animal breeding
and exploitation, forestry, fishing and hunting) closed the year with positive figures and registered a growth of 2% (INEGI, 2020a). Figure 10b shows that in the global WEF index evaluation, only 40.6% of the country’s states improved by 2020.

Figure 11 shows the results of the evaluation of the global WEF index with two maps, the small map with a scale from 0 to 1 to observe the change from 2019 to 2020 and the large map with a scale from the minimum to the maximum value obtained in the evaluation of the states to observe the best and worst evaluated, where 96.8% of the country’s states are below the average value of 0.5. Only Mexico City presents a score equal to or higher than 0.5 (2019 and 2020), which was the worst evaluated in the WEF nexus index, but was the second-best state in the IPiBpc and IPob indices. In second place in the global WEF index is Nuevo Leon, followed by Jalisco and the State of Mexico.
For 2019 and 2020, the states with red color that indicate the lowest scores in the global WEF index are Morelos, Baja California, Nayarit, Zacatecas, Colima and Tlaxcala. Tlaxcala was the worst state in the country with a decrease in the value of the WEF nexus index by $-1.74\%$ from 2019 to 2020 (Fig. 10b), besides having a low position in the ranking of the IPIBpc index in 29th place and with a decrease in its GDP in the 3 economic activities and IPob in 28th place out of 32, all of the above had repercussions in the reduction of the value of the global WEF index of $-2.5\%$.

7 Conclusions

This study has presented a new methodology that develops a composite index called Global WEF Index that involves the WEF nexus index which has nine indicators that evaluate the availability, accessibility and regional interdependence of each resource in
A systematic approach for assessing water, energy and food…

the water–energy–food nexus. The IPIBpc index involves the Gross Domestic Product per capita and the IPob index which includes the population. This methodology was applied to each state of Mexico, and the years 2019 and 2020 were analyzed, which correspond to a year before the COVID-19 pandemic was declared in Mexico and during the same pandemic to determine the security of the three resources and the economic environment. In general, the difference in results obtained between the years analyzed cannot be entirely attributed to the COVID-19 pandemic.

The results show that in the evaluation of the global WEF index of the 32 states of the country, only 13 states improved in 2020, and this is derived from the implications of the indices that compose it since 21 states improved in the evaluation of the WEF nexus security. Overall, there was an improvement in water and energy accessibility by 2020, while food accessibility shows a decrease. There was a decline in water availability and an increase in energy availability; with food, there is high availability, but there was a slight

Fig. 10 a Percentage variation of the IPIBpc index and b Percentage variation of the Global WEF Index between 2019 and 2020
decrease. However, results showed an improvement in the regional interdependence of water, energy and food in 2020.

In the evaluation of the IPIBpc index involving GDP per capita, 23 states worsened by 2020 due to the stoppage of activities as a measure to stop the spread of COVID-19, which substantially affected secondary and tertiary economic activities. To analyze the achieved results, the results of the IPIBpc and IPob indices were plotted in the form of rankings, for the WEF nexus index in stacked bar charts and the Global WEF Index in choropleth maps, which provide clear signals that alert and expose extraordinary situations and allow the identification of possible areas of intervention for the actors of interest. The global indicator can play a leading role due to its simplification, since, in general, decision-makers usually spend little time studying and analyzing the issues, demanding to present the results as concisely and synthetically as possible. Therefore, their presentation must communicate an image that facilitates quick and accurate visualization.

On the other hand, some actions can be carried out to improve the security or availability of resources, an effort should be made to implement alternative forms of water and

Fig. 11 Global WEF index results of the states in 2019 and 2020
energy generation to reduce their consumption, create awareness to make better use of resources and eat a balanced diet, generate programs to eradicate malnutrition, implement policies to punish excessive consumption of resources or encourage the reduction of greenhouse gas emissions. It is important to work on planning more resilient systems.

It is not excluded that the global WEF index can be used based on units of analysis at higher and lower levels, for example countries, states, provinces, or municipalities, or even units of analysis at the microdata level considering households or individuals.

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Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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