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An inclusive approach for integrated systems: Incorporation of climate in the water-food-energy-land nexus index

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ABSTRACT

Land and water resources are largely used for food production during agricultural activities. Some farm operations are energy intensive and climate is also affected due to the use of fossil energy during the farm operations. Thus, the nexus assessment without considering climate as an indicator may not provide a holistic outlook toward a secure, efficient, and sustainable use of resources. Therefore, this study aimed to incorporate climate as an indicator in the already existing water-food-energy-land nexus methodology. To implement the water-food-energy-land-climate nexus index, the wheat crop production system in Punjab, Pakistan was taken as a case study. Twelve different indicators were normalized and then aggregated to assess the value of the water-food-energy-land-climate nexus index. Higher the value represents better the sustainable production of crops and land suitability. The value of the water-food-energy-land-climate nexus index varied from 0.34 to 0.78 across Punjab indicating a wide range of sustainable wheat crop production and land suitability for wheat cultivation. The northwest region was showing a lower water-food-energy-land-climate nexus index value as compared to the south. The south and central Punjab areas are more suitable for the wheat crop as compared to the north or west. The water-food-energy-land-climate nexus index could also be used as a comprehensive tool to evaluate the performance of other crops as well. It can also help in formulating an inclusive policy for sustainable development goals — such as SDG 2 (elevate food security), 6 (enhance water security), 12 (responsible consumption and production), and 13 (climate action).

1. Introduction

The global population is projected to reach around 10 billion by 2050 (UN, 2019) and the intensification of stresses on resources such as water, energy, and land is likely to increase due to the need to meet the growing demand for food (SWITCH-Asia, 2022a). Global production of primary crops increased by approximately 50 % between 2000 and 2018 (FAO, 2020a). World cereal equivalent food demand is projected under a strong convergence scenario to be around 10,094 million tonnes in 2030 and 14,886 million tonnes in 2050 (Islam and Karim, 2019). The Asian continent holds the primary position in the production of cereal crops, particularly wheat and rice (Farooq et al., 2023). To meet the growing demand for cereal equivalent food, more agricultural land is required. Already, agriculture covers more than half of the Asian land area and it is further expanding due to the increase in agricultural activities.

The agricultural land expansion also causes deforestation; according to the Food and Agriculture Organization of the United Nations (FAO), the South-East Asian region lost 376 thousand km^2 of forest between 1990 and 2020 (SWITCH-Asia, 2022a). Deforestation is one of the main sources of greenhouse gas (GHG) emissions. Almost one billion ha of land would be cleared globally by 2050, with GHG emissions reaching ~3 Gt CO_2eq y^{-1} (Tilman et al., 2011). Furthermore, there are many more environmental impacts associated with agricultural activities, most of them due to the use of fossil fuels, fertilizers, pesticides, and herbicides during farm operations (Poore and Nemecek, 2018). During crop production, the use of fertilizers and other synthetic chemicals can harm marine, freshwater, and terrestrial ecosystems (Tilman et al., 2011).

The impacts of farm operations are even more in the arid and semi-arid regions as compared to the humid or wet regions mainly due to the

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irrigation from groundwater resources, conventionally powered by fossil fuels. The environmental impacts are further amplified with groundwater depletion because of the additional energy needed to pump the water due to the lowering of the water table (Rijsberman, 2006; Siddiqi and Fletcher, 2015; Karimov et al., 2022). The topography of an area also plays an important role in energy use during land preparation (Diffendorfer and Compton, 2014). The use of fossil fuels amplifies GHG emissions in crop production. Moreover, agriculture accounts for 70 % of global freshwater withdrawals (SWITCH-Asia, 2022b; FAO, 2017), which is projected to increase further to satisfy rising food demand (Alexandratos and Bruinsma, 2012; Dalstein and Naqvi, 2022). Total global water withdrawals for irrigation are projected to increase by 10 % by 2050 (FAO, 2011). Groundwater supplies the water for the world's irrigation demand at about 40 % (Siebert et al., 2010). The impacts of water withdrawal on agriculture are even more intensified in dry arid regions. Such regions may face higher water scarcity and water deprivation problems (Pfister et al., 2009).

Agriculture is a multifaceted sector that encompasses numerous elements, including land, water, and energy utilization, the production and application of fertilizers, as well as the extraction of groundwater, land preparation, etc. Mainly due to the fossil fuel-based processes agricultural activities are also linked to climate change (Lynch et al., 2021; Lad et al., 2022) which is why water, food, energy, land, and climate are interconnected comprising a coherent system (the 'Nexus'). Managing one of them cannot be considered in isolation but should be seen as part of an integrated system (Giampietro et al., 2013; European Commission, 2021a; Cremades et al., 2019). Therefore, the integrated management of Nexus is critical to securing the efficient and sustainable use of resources and developing strategies (European Commission, 2021b). The nexus approach allows for more integrated and effective policymaking, planning, monitoring, and evaluation related to the different nexus sectors (Giampietro et al., 2013; Purwanto et al., 2021; Botai et al., 2021).

There are multiple methodologies available for nexus approaches such as the method of El-Gafy (2017), the Life Cycle Assessment (LCA) based method for nexus assessment, etc. The nexus approach developed by El-Gafy (2017) and the LCA approach share some similarities, both being holistic and multidisciplinary approaches with systems thinking, data-driven analysis, and relevance for policy decisions related to sustainable development and environmental management. Both methodologies require experts from different fields to assess the interconnections and interdependencies between different systems and components within a system and to collect data on material flows, energy use, emissions, and social impacts.

On the other hand, the El-Gafy (2017) and the LCA approaches differ in their focus and scope. El-Gafy (2017) introduced a method that considers the interlinkage among various indicators, including economic and social factors such as monetary value and labor involvement, in addition to resource consumption and productivity (Jaroenkietkajorn and Geewala, 2020). However, LCA deals mainly with environmental impact indicators (Silalertruksa and Gheewala, 2018). Therefore, as a base method, the methodology of El-Gafy (2017) was utilized in this study. To provide the solution to the interlinkages, El-Gafy (2017) provided a water-food-energy nexus approach. Further, Gazal et al. (2022) improved the water-food-energy nexus methodology by adding a land indicator. The novelty of this research was to improve the nexus methodology further by incorporating climate as an indicator. Thus, this study aimed to provide a method for decision-makers to analyze and identify hotspots of the water-food-energy-land-climate nexus index (*further referred to as*; *nexus index*) of a crop production system in a holistic manner. The nexus index will be useful for policymakers to achieve sustainable development goals (SDGs). Especially, by quantifying the GHG emission in crop production along with the other indicators. The strength of the nexus index is its scope, it can be applied to all types of crops without any spatial and temporal limitations. Furthermore, the nexus INDEX can be used for the future projection of the nexus quantification for the crop production system. To apply the *nexus index*, the wheat crop in Punjab province was selected as a case study.

2. Material and methods

The section of this study is divided into three sub-segments, the first is related to the assessment of the water-food-energy-land-climate nexus, the second is associated with the data collection, and the third piece deals with the selection of the study area to apply the methodology. The first segment is further classified into nine sub-sections as discussed below.

2.1. Methodology

This research focused on assessing the interlinkage or nexus among water, food, energy, land, and climate by taking the wheat crop system. El-Gafy (2017) developed the nexus methodology as a problem-solving framework to address complex interdependencies and interactions between water, food, and energy systems. This methodology comprises six indicators, with two each belonging to water and energy in the resource use category, two in the resources economic productivity, and the last two linked with water and energy in the resources mass productivity. El-Gafy (2017) normalized all the indicators and estimated the nexus index value by applying the weighted average, which ranges from 0 to 1. A higher index value indicates sustainable consumption and production of resources. Furthermore, the nexus approach is based on the assumption that there is a close interdependence among the factors involved in the systems. Changes in one factor can have significant impacts on others. Moreover, sustainability is a key goal and the management of water, food, and energy systems should be designed to meet the needs of the present without compromising the ability of future generations to meet their own needs. Furthermore, the nexus approach is based on the principles of systems thinking, quantitative and qualitative analysis, and decision support. The method aims to provide a comprehensive understanding of the interdependencies and trade-offs between water, food, and energy systems and support decision-making for sustainable development.

Subsequently, Gazal et al. (2022) expanded the water-food-energy methodology by adding one more indicator (land) to enhance its comprehensiveness. They used seven indicators, six of which were the same as those used by El-Gafy (2017). Gazal et al. (2022) followed the same methodology for normalization and the nexus index scale as in the original approach. This study further improved the nexus index by incorporating climate indicators into the already existing water–food–energy-land nexus index methodologies used (El-Gafy, 2017; Gazal et al., 2022).

For calculating the nexus index score, twelve indicators were used and normalized to obtain the nexus index score. The indicators are as follows: water use (m^3/ha), energy use (GJ/ha), land use (ha), GHG emissions during farm operations (CO_2eq/ha), water mass productivity (t/m^3), energy mass productivity (t/GJ), land mass productivity (t/ha), mass output per unit of GHG emission (kg/kg CO_2eq), water economic productivity (USD/m^3), energy economic productivity (USD/GJ), land economic productivity (USD/ha), and economic output per unit of GHG emission (USD/kg CO_2eq). The water-food-energy-land-climate nexus index was applied to the wheat crop system, in Punjab, Pakistan as a case study. The system boundary of the assessment was taken from cradle to farm gate. While capital goods are not considered during estimation because of their extended lifespan and relatively minor role as a resource during a single crop season. Furthermore, the potential decline in water quality caused by using chemicals in crop production was not considered. In the evaluation of nexus, all indicators were given equal importance.

2.1.1. Resources use and GHG emissions

This section explained the natural resources water, energy, and land use and GHG emissions in the wheat production system, as discussed below.

I. Water use

The water use indicator (W_C) is the water use per hectare of the crop in a season.

II. Energy use

There are two types of energy usage in the farms, one is direct energy use and the second is indirect energy use. Energy consumed in the form of fuel or electricity during farm operations is considered direct energy use. The energy used during the transportation of farm inputs, outputs, and production of fertilizers and other chemicals is taken as indirect energy use. The water use (Ec) is the sum of direct and indirect energy used in the different farm operations as shown in Eq. 1.

$$E_C = \left(q_h h + q_m m + q_d d + q_f f + q_p p + q_s s + q_w w\right) \tag{1}$$

where: q_h, q_m, q_d, q_f, q_p, q_s, and q_w are respectively the energy equivalents of human labor (J/h), machinery (J/h), diesel oil (J/L), fertilizer (J/kg), pesticides (J/kg), seeds (J/kg), and irrigated water (J/m^3) inputs in crop production. Moreover, h, m, d, f, p, s, and w are respectively human labor (h/ha), machinery (h/ha), diesel fuel (L/ha), electricity (kWh/ha), fertilizer (kg/ha), pesticides (kg/ha), seeds (kg/ha), and irrigated water (m^3/ha) inputs. The energy equivalents are taken from Zahedi et al. (2015) which are given in Table S1 (Supplementary material).

III. Land use

The land use (ha) is referred to as the area under cultivation for the wheat crop for the entire season. The area under wheat cultivation for the stations under consideration was taken from the Punjab Agriculture Department (2021).

IV. GHG emissions during farm operations

This section discussed the GHG emissions from wheat production from different sources and their estimation. The GHG emissions in crop production are from the burning of fossil fuels in farm machinery, the use of electricity for groundwater pumping, the application of fertilizers in the field, fertilizer production, and the transportation of the inputs to the field. The GHG emission was estimated by multiplying activity data (fossil fuel and electricity use, application of fertilizer, production of fertilizer, and transportation) and emission factors. To estimate the GHG emission from electricity, Pakistan's electricity mix for 2020 was taken from Butt et al. (2021). Moreover, GHG emissions due to the nitrogen fertilizer application are mainly due to the N_2O emission. According to IPCC (2006) volume 4, chapter 11, there are two types of N_2O emission due to fertilizer application, direct and indirect (IPCC, 2006). This study considered both direct and indirect emissions. However, the emission factors for fertilizer production were taken from ecoinvent 3.0. Moreover, the IPCC, 2006 guidelines, volume 2, chapter 3 were used for road transportation emissions (IPCC, 2006). It was assumed that the transportation mode and type of vehicle are land transportation and 16 t lorry with a round trip, diesel is used as fuel, 7 km/L of diesel is consumed, and the distance from the field to the urban center is 15 km (one-way). The Global Warming Potential (GWP) and emission factors of fossil fuel use, electricity use, application of fertilizer, and transportation were taken from IPCC (2021) and IPCC guidelines 2006 (IPCC, 2006) respectively. Total GHG emissions due to the farm operations in terms of CO_2eq/ha were estimated by taking the product of activity data, emission factor, and GWP as shown in Eq. 2.

$$GHG = \left\{ \left(d \times EF_d\right) + \left(e \times EF_e\right) + \left(fa \times EF_a\right) + \left(fp \times EF_p\right) + 2\left(dm \times s \times EF_t\right) \right\} \times GWP \tag{2}$$

where, the diesel use, electricity use, fertilizer application, fertilizer production, fuel mileage, and distance covered to bring farm inputs from the urban center to the field are expressed with d, e, fa, fp, dm, and s respectively. Furthermore, the emission factors of diesel, electricity use, fertilizer application, fertilizer production, and transportation are represented as EF_d, EF_e, E_{fa}, E_{fp}, and EF_t respectively.

2.1.2. Resources mass productivity and mass output per unit of GHG emission

This section deals with the mass productivity of water, energy, land, and GHG emissions and mass output per unit of GHG emission. The explanation is given below.

I. Water mass productivity

Water mass productivity (W_{MP}) (m^3/ha) indicates the production of a crop in terms of mass by using the per unit of water as shown in Eq. 3. Y is the yield of a crop (t/ha) and W is the water use (m^3/ha) of a crop.

$$W_{MP} = \frac{Y}{W} \tag{3}$$

II. Energy mass productivity

Energy mass productivity (E_{MP}) (J/ha) refers to the production of a crop in terms of mass per unit of energy as shown in Eq. 4. Y is the yield of a crop (t/ha) and E is the energy use (J/ha) of a crop.

$$E_{MP} = \frac{Y}{E} \tag{4}$$

III. Land mass productivity

Land mass productivity (L_{MP}) (tonne/ha) is a measure of agricultural outputs in terms of mass obtained on a given area of land. It is the ratio of farm mass output (F_M) in tonnes to the farm planted area (F_A) in hectares as shown in Eq. 5.

$$L_{MP} = \frac{F_M}{F_A} \tag{5}$$

IV. Mass output per unit of GHG emission

Mass output per unit of GHG emission (kg/kg CO_2eq) is a measure of agricultural outputs in terms of mass obtained on the expense of per unit GHG emissions. Mass output per unit of GHG emission (GHG_{MO}) also can express the ratio of agricultural outputs (M) per unit of GHG emission (GHG) as shown in Eq. 6.

$$GHG_{MO} = \frac{M}{GHG} \tag{6}$$

2.1.3. Resources economic productivity and mass output per unit of GHG emission

This section deals with the economic productivity of water, energy, land, and GHG emissions and mass output per unit of GHG emission. The explanation is given below.

I. Water economic productivity

Water economic productivity (W_{EP}) is the ratio of return minus the cost of inputs in terms of monetary values per hectare of a crop to the volume of water consumed per hectare to grow a crop as shown in Eq. 7.

N is the monetary return per ha from the crop (USD/ha), C is the cost of inputs used (USD/ha), and W is the water used (m^3/ha) for cultivating a crop.

$$W_{EP=}\frac{N-C}{W} \tag{7}$$

II. Energy economic productivity

Energy economic productivity (E_{EP}) is the ratio of return minus the cost of inputs in terms of monetary values per hectare of a crop to the energy consumed per hectare to grow a crop as shown in Eq. 8. N is the monetary return per ha from a crop (USD/ha), C is the cost of inputs used (USD/ha), and E is the energy used (J/ha) of a crop.

$$E_{EP=}\frac{N-C}{E} \tag{8}$$

III. Land economic productivity

Land productivity (L_{EP}) is a measure of agricultural outputs in terms of monetary values at constant prices obtained on a given area of land. It is the ratio of farm volume output (F_E) in tonnes to the farm planted area (F_A) in hectares as shown in Eq. 9.

$$L_{EP}=\frac{F_E}{F_A} \tag{9}$$

IV. Economic output per unit of GHG emission

Economic output per unit of GHG emission (USD/kg CO_2eq) is a measure of agricultural outputs in terms of monetary values obtained at the expense of per unit GHG emissions. Economic output per unit of GHG emission (GHG_{EO}) also can express the ratio of agricultural monetary outputs (M_O) per unit of GHG emission (GHG) as shown in Eq. 10.

$$GHG_{EO}=\frac{M_O}{GHG} \tag{10}$$

2.1.4. Water–food–energy-land-climate nexus index

This research used the nexus index to express the interlinkage among water–food–energy-land-climate in wheat production as shown in Eq. 11. It indicates sustainable consumption and production to the decision-makers. So different sustainable development goals can be achieved by adopting an integrated policy for sustainable consumption of resources, sustainable production of food, and minimizing GHG emissions to mitigate climate change.

$$\text{Nexus index}=\frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{11}$$

where w is the weight of the indicator, X is the normalized value of an indicator, and "i" represents the different indicators such as water use, energy use, etc. In this study, it was assumed that each indicator is equally important which is why an equal weight (equal to 1 for all indicators) was assigned to each indicator. The decision to use equal or unequal weights for indicators is contingent upon the practitioner's or user's philosophy. In the absence of a strong reason for choosing different levels of importance for the various indicators, equal weights could be used. However, different weights for the indicators could also be used should there be a reason to do so. As can be understood, the choice is rather subjective and hence open to discussion. This method is flexible regarding the harmonization, either using equal or unequal weights of the indicators.

The twelve indicators (water use, energy use, land use, GHG emissions, water mass productivity, energy mass productivity, land mass productivity, mass output per unit of GHG emission, water economic productivity, economic productivity of energy, land economic productivity, and economic output per unit of GHG emission) during farm operations were normalized by applying the minimum-maximum normalization technique as shown in Eqs. 12 and 13. Eq. 12 is used when the highest value of an indicator is the most preferred and Eq. 13 is used when the least value is the most preferred. Such as the land, water, and energy productivity values should preferably be maximum, these indicators should be normalized by using Eq. 12. Moreover, as energy and water use should be the least in crop production, these indicators should be normalized by using Eq. 13.

$$X_i=\frac{x_i-Min\ (x_i)}{Max\ (x_i)-Min\ (x_i)} \tag{12}$$

$$X_i=\frac{Max\ (x_i)-x_i}{Max\ (x_i)-Min\ (x_i)} \tag{13}$$

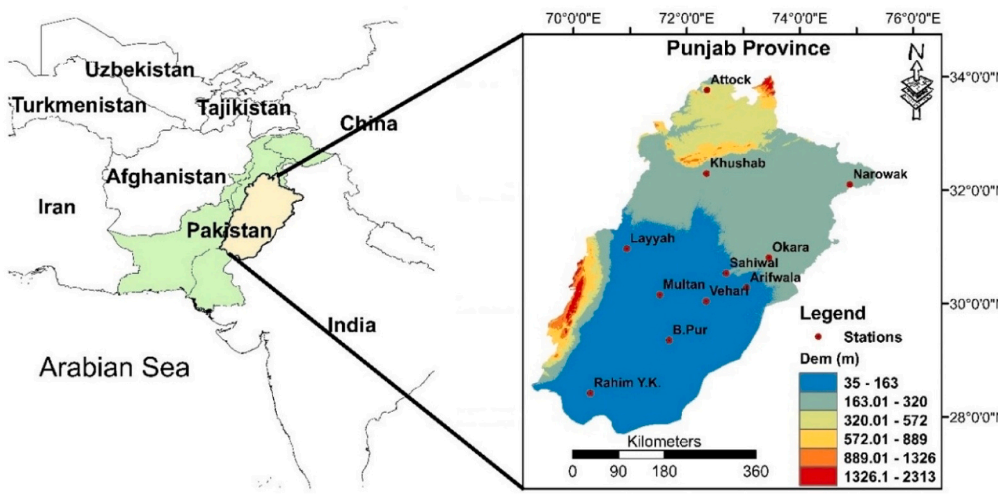
The minimum ($Min\ (x)$) and maximum ($Max\ (x)$) values were taken as the lowest and highest values from the dataset against each indicator. Where "x" represents the data point value and "i" represents the different indicators such as water, energy use, etc. While X represents the normalized value of an indicator.

2.2. Data acquisition

To conduct this study, data was obtained by interviewing farmers cultivating wheat. During the interview, questions were asked about the inputs and outputs of wheat farming. To include spatial variation in data, the survey was conducted across Punjab province, Pakistan. Moreover, to capture the variations due to agricultural practices, four to five farmers were interviewed in different villages throughout Punjab. The 42 wheat fields were selected randomly from 11 main cities in the studied region in 2021; the conversion rate was 160 Pakistani rupees per USD at that time. The data inventory is provided in Table S2 (supplementary material).

2.3. Study area

Wheat is one of the main cereal crops; in 2020 global wheat production reached up to 761 million tonne harvested over 219 million ha of land (FAOSTAT, 2022). Pakistan is the 8th largest producer of wheat (FAO, 2020b) and the Punjab province contributes 75 % of the total wheat production of the country (USDA, 2022). Wheat is the largest crop in Pakistan by area of cultivation and production which are 9.17 million ha and 27.46 million tonnes, respectively (Pakistan Bureau of Statistics, 2022). Most of the area in the province is plain but the northwest and southwest area are mountainous. The topographical map of Punjab using the digital elevation model (DEM) is shown in Fig. 1. Punjab has fertile farmlands irrigated by one of the largest contiguous irrigation systems in the world (Basharat, 2019). The colossal irrigation conveyance network is serving 21.71 million acres (8.79 million ha). Wheat, sugarcane, cotton, rice, and maize are the main crops. Over 50 % of Punjab's workforce and 20 % of the GDP come from agriculture (PMU, 2017). The mean annual maximum temperature varies from 28 to 33 °C. The mean annual minimum temperature range is almost uniform range of 16 to 18 °C. The mean annual precipitation varies from 768 to 965 mm in the northern 126–216 mm in the southern part (Khattak and Ali, 2015; Akbar and Gheewala, 2020). The southern part is drier and hotter as compared to the north. Based on these characteristics the wheat crop system in Punjab, Pakistan was selected as a case study. Because wheat is the largest crop in Pakistan by area of cultivation and production were 9.17 million ha and 27.46 million tonnes respectively (Pakistan Bureau of Statistics, 2022).



*DEM = digital elevation model

Fig. 1. Topography of Punjab province, Pakistan.
*DEM = digital elevation model.

3. Results and discussion

This study evaluates the use of resources (water, energy, and land) for the production of food (wheat crop), and GHG emissions during farm operations by using the nexus index. This section can be divided into two main parts; the first discusses the inputs of resource use, productivity, food production, and GHG emissions, and the second one relates to the nexus index evaluation.

3.1. Resources use and GHG emission

Water, energy, land, chemicals, and seed are the main inputs used but at the same time GHG emissions for wheat crop production. The spatial variation in the water use, energy use, land use, and GHG emission for the wheat crop system is shown in Fig. 2 across Punjab.

I. The water use for wheat crop production varied from 2170 to 4660 m^3/ha. The average water use for the wheat crop was 3371 m^3/ha was assessed. Water use was higher in the southeast portion of Punjab. The lowest water use was noticed in the northwest part of Punjab.
II. Moreover, the energy use during the entire season of wheat crop in Punjab varied from 21.1 to 30.5 GJ/ha. The average energy use for the wheat crop was 26.3 GJ/ha. The energy use in southern Punjab was higher as compared to the northern side. The total energy use was the sum of energies from electricity, human labor, machinery hours, diesel used, fertilizers, herbicides, pesticides, seeds, and water as shown in terms of percentage in Fig. S1 (Supplementary material).
III. Land use is a crucial factor in wheat crop production, and this section focuses on the total land area in millions of hectares for various stations under consideration. The lowest and highest areas under cultivation for the wheat crop were recorded at Arifwala and Bahawalpur stations, respectively, with 0.111 and 0.301 million ha of land dedicated to wheat cultivation.
IV. The GHG emission during farm operations was used as a proxy for climate change. GHG emission was estimated by adding the emission from different farm operations viz. emissions from groundwater pumping, soil preparation, crop harvesting, fertilizer applications, fertilizer production, and transportation of chemicals and seeds, etc. It was noticed that the GHG emission varied from 1579 to 2278 kg CO_2eq/ha. The average GHG emissions from the wheat crop were estimated at 1872 kg CO_2eq/ha. The GHG emission in southern Punjab was relatively higher as compared to the northern side. The lowest GHG emission was noticed in the northwest of the region. Almost 70 % of emissions

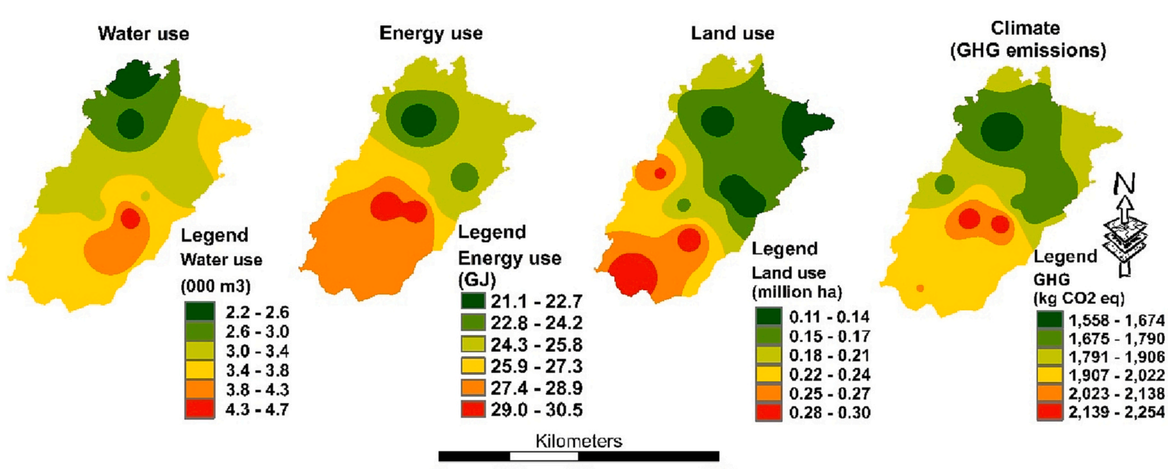


Fig. 2. The spatial variation in water, energy, land use, and GHG emission for the wheat crop system.

come from the only fertilizer application and production for the wheat crop. Nearly 11 % of GHG emissions are from electricity use for groundwater pumping. The GHG emission from diesel use contributed almost 19 % to the total. Diesel is mainly used in soil preparation and to somehow for groundwater pumping as well as in farm operations. The GHG emission from transportation was minor as shown in Fig. S2 (Supplementary material).

Furthermore, chemicals and seeds are also used in wheat crop production. On average seed, pesticides, herbicides, urea, di-ammonium phosphate (DAP), and potash for wheat production were used 119 (kg/ha), 741 (ml/ha), 710 (ml/ha), 256 (kg/ha), 190 (kg/ha), and 31 (kg/ha), respectively.

3.2. Resources productivity

Mainly the two types of resource productivities are used in this study; mass productivity and economic productivity, and land productivity. However, mass productivity was further dealt with water mass productivity, energy mass productivity, land mass productivity, and per unit of GHG emission for mass productivity. Similarly, economic productivity was further split into water economic productivity, energy economic productivity, land economic productivity, and per unit of GHG emission for economic productivity. Further details are discussed below. The spatial variation in the water mass, energy mass, land mass productivities, and mass output per unit of GHG emission for the wheat crop system is shown in Fig. 3 across Punjab.

3.2.1. Resources mass productivity and mass output per unit GHG

This section deals with the mass productivity of resources and mass output per unit GHG.

I. The water mass productivity

Water mass productivity (kg/m^3) is the measure of crop production in terms of mass (kg) per unit volume of water consumed (m^3). The water mass productivity for wheat production varied from 1.0 to 1.6 kg/m^3 and the average water mass productivity was 1.3 kg/m^3. The water mass productivity was the highest in the southern part of Punjab but, it was lower in the northeast and western border of Punjab and moderate in the central part of Punjab. The spatial variation in the water mass productivity can be due to the different climatic zones, soil fertility, topography, availability of surface water, and groundwater.

II. The energy mass productivity

Energy mass productivity (kg/MJ) is the measure of crop production in terms of mass (kg) per unit of energy consumed (MJ). The energy mass productivity for wheat production varied from 0.12 to 0.20 kg/MJ and the average energy mass productivity was 0.17 kg/MJ. It was noticed that energy mass productivity was lower in the northwest corners of Punjab, while it was higher in the southern and eastern regions. The energy mass productivity was lower in the northwest due to the low soil productivity, lack of surface water, and extra energy requirement for groundwater pumping in dry months which causes lower crop yield per energy use. However, the energy mass productivity was higher in the southern region because of intensive irrigation infrastructure availability (canal system), and better soil fertility in this region.

III. The land mass productivity

Land mass productivity (kg/ha) is the measure of crop production in terms of mass (kg) per unit of land use (ha). Land mass productivity was estimated with the help of the survey conducted across Punjab. It was found that the land mass productivity varied from 2.7 to 5.9 t/ha and the average value was 4.4 t/ha. It was noticed that the land mass productivity was the lowest in the northwest region possibly due to the mountainous terrain, lack of surface water infrastructure (canal system) for dry months, and small farm size which limit the farmer to modernize the farms and lower the soil fertility of the area. However, it was the highest in the southern and southeast parts of Punjab possibly due to the intensive irrigation infrastructure (canal system), suitable topography, better soil fertility, and larger farm size which helps the farmers to invest to modernize the farm for better productivity.

IV. Mass output per unit of GHG emissions

Mass output per unit of GHG emissions (kg/kg CO_2eq) is a measure of crop production in terms of mass (kg) per unit of GHG emission (kg CO_2eq). It was noticed that it varied from 1.6 to 2.8 kg/kg CO_2eq. The average mass output per unit of GHG emissions during the wheat crop was estimated at 2.3 kg/kg CO_2eq. The mass output per unit of GHG emissions in the northern area of Punjab was relatively lower as compared to the central and southern sides.

3.2.2. Resources economic productivity and mass output per unit GHG

This section deals with the economic productivity of resources and economic output per unit GHG.

I. The water economic productivity

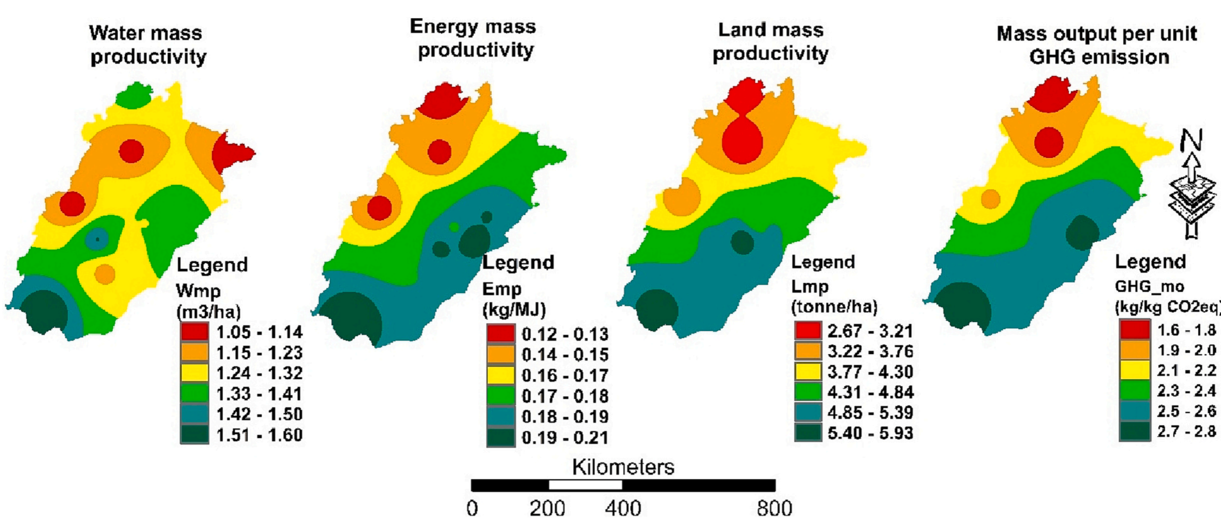


Fig. 3. The spatial variation in water mass, energy mass, land mass, productivity, and mass output per unit of GHG emission for the wheat crop system.

Water economic productivity (USD/m^3) is the measure of economic output (USD) per unit volume of water consumed (m^3). The water economic productivity for wheat production varied from 0.17 to 0.26 USD/m^3 and the average water economic productivity was 0.21 USD/m^3. The spatial variation of water economic productivity is shown in Fig. 4. The southwest part of Punjab showed higher water economic productivity but, the northeast and northwest parts of Punjab showed lower values. The lower water economic productivity especially in the northeast side was most probably due to differences in climatic conditions (relatively colder) and soil type (clay). For wheat production, silt loam soil is the most suitable soil type (Jalota et al., 2010). Moreover, the water economic productivity in the southwest region was relatively higher possibly due to the better soil productivity, and availability of intensive irrigation infrastructure (canal system).

II. The energy economic productivity

Energy economic productivity (USD/MJ) is the measure of economic output (USD) per unit of energy consumed (MJ). The energy economic productivity for wheat production varied from 0.02 to 0.03 USD/MJ and the average value was 0.03 USD/MJ. The spatial variation in energy economic productivity is shown in Fig. 4; it was lower in the northwest and western regions and higher in the eastern and southern regions of Punjab. Lower energy economic productivity was mainly due to the lower soil fertility, higher dependency on groundwater for irrigation, and ultimately lower crop yield in the northwest region as compared to the other parts of Punjab. On the hand, the southern part showed higher energy economic productivity, mainly because of the higher yield of the crop.

III. The land economic productivity

Land economic productivity (USD/ha) is the measure of crop production in terms of monetary values (USD) per unit of land use (ha). Land economic productivity was estimated with the help of the survey conducted across Punjab. It was found that the land economic productivity varied from 417 to 927 USD/ha. The spatial variation in the land economic productivity is shown in Fig. 4 and the average value was 709 USD/ha. It was noticed that the land economic productivity was the lowest in the northwest region possibly due to the mountainous terrain, lack of surface water infrastructure (canal system) for dry months, and small farm size which limit the farmer to modernize the farms and lower the soil fertility of the area. These factors can lead to the lowering crop yield mean lowing the economic output. However, it was the highest in the southern and southeast parts of Punjab possibly due to the intensive irrigation infrastructure (canal system). Which leads to the higher economic output.

IV. Economic output per unit of GHG emissions

The economic output per unit of GHG emissions (USD/kg CO_2eq) is a measure of crop production in terms of monetary numbers (USD) per unit of GHG emission (kg CO_2eq). It was noticed that it varied from 0.3 to 0.5 USD/kg CO_2eq. The average economic output per unit of GHG emissions was estimated at 0.4 USD/kg CO_2eq during the wheat crop. The economic output per unit of GHG emissions in the northwest area of Punjab was the lowest while in central Punjab was the highest respectively. The spatial variation in the economic output per unit of GHG emissions is shown in Fig. 4.

3.3. Water–food–energy-land-climate nexus index

The nexus index was formulated to solve the problems related to resource efficiency in an integrated way, not in an isolated manner to get the maximum yield. As this nexus index gives quantitative insight into the use of water, energy, land, and other inputs for food production. The mean value of the twelve indicators and the final nexus index is shown in Fig. 5 along with the 95 % confidence level. The margin of error was used to quantify the uncertainty in the mean values of normalized indicators and nexus index value. The margin of error refers to the amount of error or uncertainty that is expected in a statistical sample's results due to random sampling variations. It represents the range of values

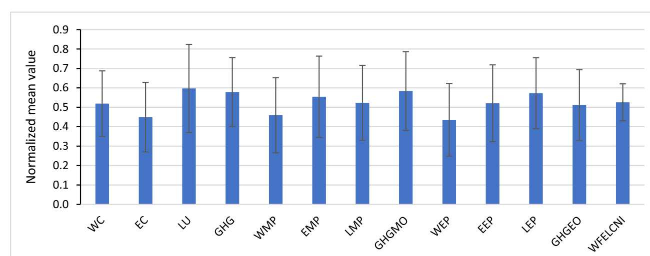


Fig. 5. Normalized mean values of the indicators and nexus index.
*Water use (W_C), energy use (E_C), land use for wheat crop (L_U), GHG emission per ha (GHG), water mass productivity (W_{MP}), energy mass productivity (E_{MP}), land mass productivity (L_{MP}), mass output per unit of GHG emissions (GHG_{MO}), water economic productivity (W_{EP}), energy economic productivity (E_{EP}), land economic productivity (L_{EP}), economic output per unit of GHG emissions (GHG_{EO}), and water–food–energy-land-climate nexus index (WFELCNI).

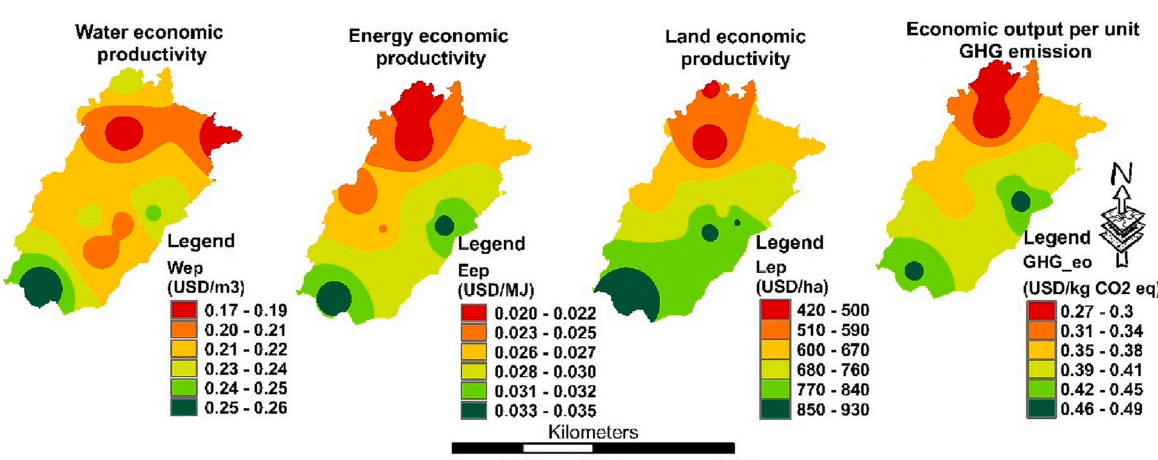


Fig. 4. The spatial variation in water economic, energy economic, land economic productivity, and economic output per unit of GHG emission for the wheat crop system.

within which the true population parameter is expected to lie (Puisa et al., 2023). The average value of the nexus index was estimated at 0.53 ± 0.095 with a 95 % confidence level. The bars in Fig. 5 represent the average values of the indicators and nexus index, while the error bars show the range of values expected for the true population parameter with 95 % confidence. The value of the nexus index varied from 0.34 to 0.78 across Punjab. The spatial variation of the nexus index is shown in Fig. 6b. The index value ranges from 0 to 1. Zero represents the worst case, while 1 represents the best case.

According to the results, a higher index value was noticed in the southern and eastern regions of Punjab. On the other hand, a lower index value was observed in the northeast and western regions of the province. The higher index value on the southern side is mainly due to the better soil fertility, (loamy soil) availability of intensive irrigation infrastructure, larger farm size, and more mechanized, and suitable terrain. On the contrary, the index value was lower in the central-west region. It was mainly due to the lower soil fertility, and intensive dry weather conditions of the area. It is because the western side of the study area is situated in the Thal desert (Fatima et al., 2019). Moreover, the northeast part was also showing a lower index value may be due to the variation of the different climatic zone and soil types (clay). On the whole, the lower index value in the northern region was due to lower energy mass productivity, energy economic productivity, land mass productivity, lower mass and energy output per unit GHG emissions, and lack of irrigation water in dry months, especially in the arid region (west part of Punjab).

3.4. Discussion

The method of El-Gafy, 2017 integrates social and economic factors. The water-food-energy nexus method recognizes that water, food, and energy systems are closely linked to social and economic factors, such as monetary value, labor involvement, etc. Further, Gazal et al. (2022) expanded the water-food-energy methodology by adding one more indicator (land) to enhance its comprehensiveness. Gazal et al. (2022) consideration to three indicators for water and three indicators for energy, but only one indicator for land was considered. This unequal distribution may diminish the significance of land and amplify the significance of water and energy. Moreover, both methodologies (El-Gafy (2017) and Gazal et al. (2022)) do not consider the environmental aspect. The GHG emission from the agriculture sector is significant (Pradhan et al., 2019), without considering it, sustainable consumption and production cannot be assessed accurately.

Therefore, this study took the method developed by El-Gafy (2017) to further improve the nexus methodology. Hence, the novelty of this work was in the incorporation of three indicators of climate (GHG emissions, Mass output per unit of GHG emissions, and Economic output per unit of GHG emissions) and three indicators of land so that the drawback in Gazal et al. (2022) methodology can be removed. Moreover, a comparative analysis was also offered between the methodologies of developed by El-Gafy (2017) and the nexus index.

The results of this study discuss the interlinkage among land, water, and energy use, GHG emission for wheat crop production, and their quantification. Moreover, the results also identified potential areas for the relatively sustainable production of crops by using the nexus index. Furthermore, relatively unsustainable production of agricultural crop areas was also identified, which also shows the pathway to improvement by different means such as technological improvements, policies shift, relocating the crop to a suitable cultivating area, etc. Despite its strengths, this study has several limitations. For instance, capital goods were excluded from the estimation due to their long lifespan and limited contribution to crop production within a single season. Additionally, the study did not consider the degradation of water quality caused by chemical applications during crop production, and it did not incorporate field emission factors, relying instead on those reported in IPCC reports.

Land use, water use, energy use, and GHG emissions during farm operations for wheat cultivation are interlinked. For sustainable consumption and production, all these factors need to be considered simultaneously. The land mass productivity of Arifwala, Bahawalpur, and Multan was almost equal, however, the value of the nexus index for Arifwala, Bahawalpur, and Multan were 0.78, 0.45, and 0.51 respectively. This shows that only the higher yield of an area cannot express the sustainable production or suitable cultivated area for that particular crop cultivation. A higher index value represents more sustainable consumption and production of the resources in an area. The normalized values of each indicator and nexus index against each station are given in Table 1.

According to the water–food–energy nexus index used by El-Gafy (2017), the western, northeast, and central regions showed a lower index value as compared to the southern region. Higher water–food–energy nexus index value represents a relatively more sustainable consumption of water and energy resources and a more sustainable production of food.

According to the nexus index used in this study, the western and northwestern regions of Punjab showed a relatively higher index value as compared to the methodology used by El-Gafy (2017). According to

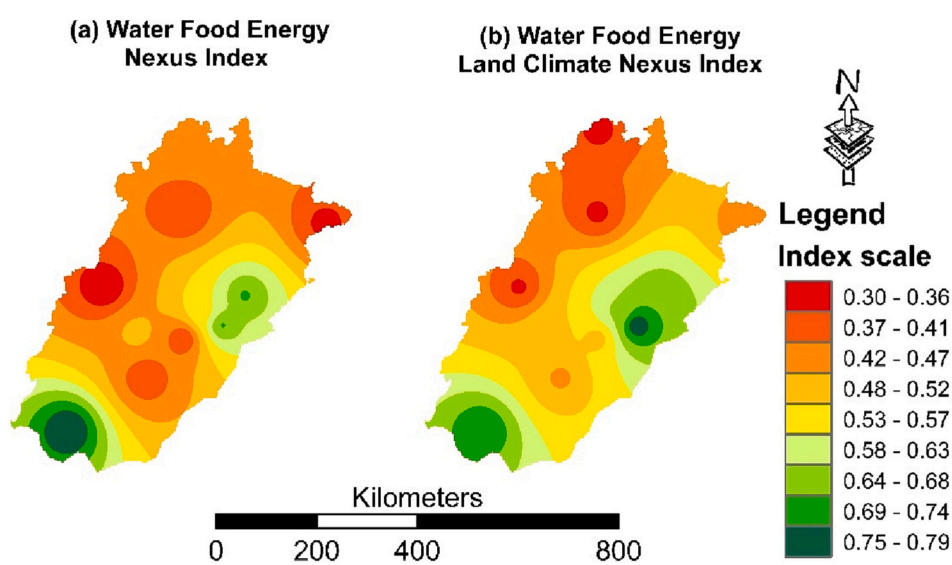


Fig. 6. The variation in nexus results due to the (a) water-food-energy nexus index and (b) water-food-energy-land-climate nexus index.

Table 1
The normalized values of each indicator and nexus index for wheat crop production.

Stations	Normalized indicators												Nexus index
	Resources use				Mass productivity				Economic productivity				
	W_C	E_C	L_U	GHG	W_{MP}	E_{MP}	L_{MP}	GHG_{MO}	W_{EP}	E_{EP}	L_{EP}	GHG_{EO}	
Arifwala	0.46	0.48	1.00	0.75	0.65	0.84	0.70	1.00	0.76	0.94	0.85	1.00	0.78
Attock	1.00	0.55	0.52	0.63	0.58	0.00	0.09	0.00	0.61	0.00	0.15	0.02	0.35
Khushab	0.90	1.00	0.91	1.00	0.10	0.11	0.00	0.06	0.01	0.02	0.00	0.00	0.34
Sahiwal	0.52	0.51	0.93	0.71	0.49	0.64	0.55	0.73	0.53	0.67	0.64	0.69	0.63
B.Pur	0.20	0.24	0.00	0.46	0.26	0.67	0.70	0.76	0.20	0.60	0.73	0.63	0.45
Narowak	0.35	0.66	0.99	0.62	0.00	0.52	0.39	0.44	0.00	0.51	0.45	0.40	0.45
Vehari	0.00	0.00	0.57	0.00	0.41	0.89	1.00	0.82	0.19	0.67	0.91	0.55	0.50
RYK	0.46	0.31	0.02	0.33	1.00	1.00	0.91	0.95	1.00	1.00	1.00	0.86	0.74
Okara	0.61	0.76	0.79	0.78	0.66	0.84	0.55	0.79	0.54	0.73	0.55	0.62	0.68
Layyah	0.66	0.41	0.14	0.87	0.06	0.06	0.18	0.28	0.36	0.26	0.39	0.48	0.35
Multan	0.56	0.01	0.71	0.21	0.84	0.53	0.70	0.59	0.60	0.35	0.64	0.38	0.51

Water use (W_C), energy use (E_C), land use for wheat crop (L_U), GHG emission per ha (GHG), water mass productivity (W_{MP}), energy mass productivity (E_{MP}), land mass productivity (L_{MP}), mass output per unit of GHG emissions (GHG_{MO}), water economic productivity (W_{EP}), energy economic productivity (E_{EP}), land economic productivity (L_{EP}), economic output per unit of GHG emissions (GHG_{EO}), and water–food–energy-land-climate nexus index (WFELCNI).

the nexus index, the suitability of wheat production in the western and northwestern regions is not as bad as estimated by the method following El-Gafy (2017). On the other hand, the nexus index showed a slightly lower index value in south Punjab as compared to the methodology used by El-Gafy (2017). This comparison shows that incorporating the land and climate indicators also plays a crucial part in nexus assessment for land suitability and zoning for a specific crop and sustainable consumption and production to achieve SDG 12. The nexus approach can provide a more comprehensive and realistic outlook toward a secure, efficient, and sustainable use of resources by adding GHG emissions as a climate indicator. However, this comparison shows that the southern and eastern regions of Punjab are the most suitable zones for wheat cultivation. The spatial variations in the water-food-energy nexus index and water-food-energy-land-climate nexus index are shown in Fig. 6a and b, respectively.

Through the results of this study, it can be recommended to the policymakers to encourage wheat crop farming in the eastern and southern parts of Punjab for relatively sustainable production of wheat crop. Moreover, the policymakers should focus on the western, northeast, and northwest regions of Punjab to utilize the resources in a sustainable way for wheat crop production by taking different adaptations or allocating these regions for some other crop that shows better index value. The methodology of this study can be applied worldwide for comprehensive nexus assessment of multiple agriculture crops.

Moreover, the higher sustainable consumption of resources and production of food can be achieved by shifting conventional irrigation to high efficiency irrigation system (HEIS), so that water productivity can be improved, shifting tube wells from diesel powered to solar, and encouraging the use of organic fertilizer along with synthetic among the farmers to reduce energy use and improve energy productivity. Moreover, replacing part of the chemical fertilizer with organic fertilizer can also help to reduce GHG emissions. The quantification of the resources for the wheat crop in Punjab, Pakistan is discussed below. Furthermore, how much resources can be preserved by implementing different policies is also discussed below.

According to Rasul et al. (2021) and the Agriculture Department (2021), the area sown under wheat crop was 6.75 million ha in 2021 which is almost 40 % of the total net area sown in Punjab, Pakistan. However, the results of this study illustrate that the wheat crop consumed 3371 m^3/ha. Therefore, it can be estimated that total water use was approximately 22.75 billion m^3 for wheat crop production in Punjab. Water use can be reduced by 20 % by only shifting irrigation systems from conventional to HEIS (Gilley and Watts, 1977). By using the HEIS, in absolute numbers, 4.55 billion m^3 of water can be saved.

According to the results of this study, the average water mass productivity is 1.3 kg/m^3. This means that 4.55 billion m^3 of water can be enough for extra 5.9 million tonnes of wheat production which may help to improve food security and achieve SDG 2. In terms of monetary value, 4.55 billion m^3 of water can generate a wheat crop having a value of 956 million USD/crop. Which can be helpful to achieve SDG 8. The average water use of the wheat crop was 3371 m^3/ha for Punjab. By only shifting from conventional irrigation to HEIS, a further 1.3 million ha of bare land can be converted into agricultural land which may help to support the ecosystem as well along with agricultural production.

The water deprivation potential is an important tool to assess the water use impacts on human beings and ecosystems (Farooq and Gheewala, 2019). The 22.75 billion m^3 used for wheat crop production in Punjab, can also have a significant water deprivation potential (water scarcity footprint) which is measured in m^3 H_2Oeq Pfister et al. (2009) and Ghani et al. (2019) explained that water deprivation potential is the product of water used and the water scarcity index. The water scarcity index value for Pakistan was obtained from Pfister et al. (2009); it is around 0.97 and the water used in wheat crop production in Punjab was 22.75 billion m^3. Therefore, the water deprivation potential was nearly 22.07 billion m^3 H_2Oeq. By implementing HEIS the water deprivation potential can be reduced almost 4.41 billion m^3 H_2Oeq which may help to reduce water stress or water deprivation, which can be helpful to achieve indicator 6.4.2 (level of water stress) of SDG 6.

This study also discussed energy use, energy use per kilogram of wheat production, and energy use to earn a dollar from wheat production. The average energy use for wheat production was 26.3 GJ/ha area. The area sown under wheat crop was 6.75 million ha in 2021, therefore the total energy use for the wheat production of Punjab was nearly 177 PJ. The most energy-intensive input was fertilizers which contribute almost 51 % of total energy use. The second highest energy use was due to diesel use for the farm operations such as soil preparation, groundwater pumping, etc. It contributes almost 14 % to the total energy use. Tube wells were also powered by electricity but the dominant by diesel-powered. According to Ali and Akbar (2021), diesel-powered tube well is 83 % and the remaining almost 17 % are fueled by electricity. Kargwal et al. (2022) discussed the energy use for wheat production in India, Australia, and Turkey which are 14.3, 10.9 GJ, and 35.7 GJ/ha respectively. Similarly, the energy use for wheat production in Iran and New Zealand is 35.5 and 25.5 GJ/ha respectively (Ziaei et al., 2015; Safa et al., 2011). The energy use for wheat production of Pakistan was significantly higher than India and Australia but lower than Iran and Turkey and New Zealand.

However, the total energy use can be reduced significantly by shifting from synthetic fertilizers to organic fertilizers for wheat production. There is no organic fertilizer policy formulated by the Agriculture Department of Punjab, Pakistan yet. However, the Agriculture Department of Punjab, Pakistan is formulating a policy for solar irrigation tube well. Govt of Pakistan is planning to switch 1.3 million tube wells in the country to solar energy from electricity and diesel (Cheema, 2022). In the case of the implementation of the solar tube well policy, approximately, 17.3 PJ of energy can be saved during wheat production in Punjab. The 17.3 PJ are equivalent to 2.8 million barrels of diesel which are roughly equivalent to 400 million USD. Moreover, the 2.2 Mt CO_2eq GHG emissions can also be reduced by saving 17.3 PJ of energy from diesel.

The contribution of GHG emissions from wheat crop production cannot be overlooked. The average GHG emission was approximately 428 kg CO_2eq/tonne of wheat production. On average, the GHG emission for the cultivation of wheat crop was approximately 1.86 tonne CO_2eq/ha. According to Rasul et al. (2021), the area of Punjab sown under wheat crop was 6.75 million ha which has a potential of GHG emission equaling 12.56 Mt CO_2eq in a crop season. Mainly fertilizer application and production are responsible for the GHG emission. These two factors combined contribute 70 % of emissions. It is recommended to the policymakers of the Agriculture Department of Punjab, Pakistan to formulate an organic fertilizer policy to minimize the environmental burden due to crop production.

This study will be helpful for the policymakers of agriculture, water resources, and climate change departments. This study will be helpful in the integrated policymaking to achieve SDG 2 (zero hunger), SDG 6 (clean water and sanitation for all), SDG 8 (decent work and economic growth), SDG 12 (responsible consumption and production), and SDG 13 (to combat climate change and its impacts by taking urgent action).

4. Conclusion

This study provides insightful detailed information on the relationship among the water, food, energy, land, and climate nexus for wheat production in Punjab, Pakistan. The research work was carried out by applying the water-food-energy-land-climate nexus index (nexus index) approach. The main contribution of this study was to improve the nexus assessment by incorporating two indicators of land and three indicators of climate (greenhouse gas (GHG) emissions considered as a proxy of climate) in the existing methodology. Which enhances the accuracy and comprehensiveness of the assessment of the agricultural system. Moreover, the results of this study illustrate, which indicators need to be improved and where with the help of spatial variation assessment for the sustainable production of wheat crop.

The average water use, energy use, land use, and GHG emissions were 3371 m^3/ha, 26.26 GJ/ha, 0.188 million ha, and 1.86 t CO_2eq/ha respectively. Moreover, the average water mass, energy mass, and land mass productivity and mass output per unit of GHG emission were 1.30 kg/m^3, 0.17 kg/MJ, and 4.38 t/ha and 2.3 kg/kg CO_2eq, respectively. The indicators deal with economic benefit; water economic, energy economic, and land economic productivity and economic output per unit of GHG emission were 0.21 USD/m^3, 0.03 USD/MJ, and 709 USD/ha and 0.38 USD/kg CO_2eq, respectively, for the wheat crop cultivation in Punjab, Pakistan.

Based on the results, it can be summarized that for wheat crop production in Punjab, the water productivity especially in the western and northwestern parts was quite low. Water productivity can be improved by switching conventional irrigation systems to modern high-efficiency irrigation systems. The northwest of Punjab showed lower energy mass and economic productivity as compared to the rest of the study area. The low energy productivity in the northwest region was mainly due to the heavy dependence on groundwater in the dry months, and the extra energy required in land preparation because of the mountainous landscape. Energy use can be reduced by rainwater harvesting and shifting tube wells from fossil fuel to solar powered. Moreover, energy use can also be reduced by replacing part of the chemical fertilizer with organic fertilizer. The GHG emissions are also linked to energy and fertilizers used in crop cultivation. The GHG emissions can also be reduced by replacing part of the chemical fertilizer with organic fertilizer. The land productivity was also almost half in the northwest region as compared to the southern region. The main reason for lower land productivity was the small farm size in the northwest. However, land productivity can also be improved by giving some attractive incentives and subsidies by the policymakers to the farmers holding small farms.

By comparing the outcome of the nexus index with the already existing water-food-energy nexus index. It was found that nexus index values were relatively higher in the low-performing area as compared to the water-food-energy nexus index. Moreover, the nexus index values were relatively lower in the higher performing area as compared to the water-food-energy nexus index. The difference is significantly visible for the north and west regions of the study area.

Furthermore, it is recommended to assess the nexus index for the other crops such as rice, cotton, maize, millet, sugarcane, olive, etc. So, zoning can be done for the appropriate crop for an area to achieve sustainable agriculture and economic growth by sustainably consuming the resources. Moreover, the projected water-food-energy-land-climate nexus assessment should be done by considering the climate change and socioeconomic scenarios for future insightfulness.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2023.05.005.

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