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Analyzing sustainable cotton production in Türkiye through the water energy carbon nexus framework

Ömer Ertuğrul[1]✉, Gülden Özgünaltay Ertuğrul[1], Adnan Değirmencioğlu[2] & Seher Kadirova[3]

The Water-Energy-Carbon (WEC) nexus provides an integrated framework for analyzing interdependent resource demands in agriculture. This study employs a comprehensive WEC-based approach to evaluate sustainable cotton production in Türkiye, focusing on water use (blue and green), energy consumption, and associated carbon emissions across varying land sizes and future renewable energy scenarios. A composite WEC Index was constructed to enable scenario comparison, where lower index values indicate improved sustainability performance under the defined normalization scheme. Projections for two periods (until 2040 and 2041–2070) assess the impacts of climate-induced precipitation changes, land expansion, and renewable energy adoption. Results show increasing water and energy demands with enlarged cultivation areas, along with a significant rise in total carbon emissions, particularly beyond 2040. Although national renewable energy targets (15% by 2040, 50% by 2041–2070) contribute to reducing the carbon intensity of energy use, they are insufficient to fully offset emissions under large-scale land expansion scenarios. The study highlights the need for coordinated land-use planning, irrigation efficiency improvements, and renewable energy integration strategies to support sustainable cotton production under future climate constraints.

Keywords WEC nexus, Cotton, Resource allocation, Virtual water, Self-sufficiency, Sustainable agriculture

The latest report on Sustainable Development Goals of the United Nations includes important goals to achieve food and water security that are irrefutably in relation with sustainability in agriculture[1]. In this respect, agricultural production needs to be analyzed considering all resources and their relations to quantify and analyze the inter-linkages of water and energy systems to accomplish sustainability in food production[2,3].

Water, energy, and food security issues are rapidly developing problems in the Middle East and Mediterranean areas[4,5] since the competition for water between cities and agriculture increases. Further research is required to evaluate the trade-offs associated with the allocation of resources to dominant crops, such as cotton. This is particularly pertinent in the context of growing concerns about its high water consumption, and ongoing discussions about reducing cotton production in Türkiye[6].

Türkiye is ranked sixth in world cotton production and the fifth as a cotton importer in the world[7]. Through the international trade of cotton, the virtual flow of resources occurs. Exporting countries utilize substantial quantities of water and energy in the production of goods, thereby effectively externalizing the environmental burden and conserving domestic resources in import-oriented nations[8].

Recent studies have extensively examined the water footprint of various agricultural products. Lee et al. (2019)[9] assessed domestic rice distribution in Japan by integrating virtual water trade to inform transboundary water-food management strategies[9], while Abdelkader et al. (2018)[10] introduced a national modeling framework to evaluate water-food-trade dynamics in Egypt[10]. Similarly, Mekonnen and Hoekstra (2011)[11] and Bulsink et al. (2010)[12] provided comprehensive global and regional water footprint estimations for major crops, including cotton, highlighting spatial variations in green and blue water consumption. Green water refers to effective precipitation stored in the soil and used directly by crops, while blue water refers to surface and groundwater used for irrigation[11]. Ene et al. (2012) applied water footprint accounting to Romanian agriculture[13], while Hanasaki et al. (2010)[14]utilized global hydrological modeling to quantify virtual water flows, emphasizing the

[1]Faculty of Agriculture, Department of Biosystems Engineering, Kırşehir Ahi Evran University, 40100 Kırşehir, Türkiye. [2]Faculty of Agriculture, Department of Agricultural Engineering and Technologies, Ege University, 35100Bornova, Izmir, Türkiye. [3]Faculty of Electrical Engineering, Electronics and Automation, Department of Automatics and Electronics, University of Ruse "Angel Kanchev", Ruse 7017, Bulgaria. ✉email: oertugrul@ahievran.edu.tr

role of precipitation variability[14]. These studies contributed to a growing understanding of water resource use in agriculture; however, they often treated water independently of other critical inputs like energy or emissions.

Regarding energy analysis, Yilmaz et al. (2005)[15] and Canakci et al. (2005)[16] investigated the energy use patterns of cotton and other field crops in Türkiye, focusing on operational energy efficiency. Nonetheless, these assessments lacked integration with other environmental factors, such as water and carbon emissions, thus limiting their utility for comprehensive sustainability assessments.

In response to the growing demand for multidimensional resource analysis, recent literature has shifted toward nexus-based frameworks, particularly the Water–Energy–Food (WEF) nexus, which emphasizes the interdependence between water, energy, and food systems. Adebiyi et al. (2020)[17] explored the water-food-energy-climate nexus in Nigeria through organic vegetable production[17], while Aliewi and Alomirah (2020)[18] and Vittorio (2020)[19] applied WEF analysis to assess policy implications in Kuwait and Saudi Arabia, respectively. Akbari-Dibavar and Mohammadi-Ivatloo (2020)[20] and Saif et al. (2020)[21], focusing on case studies from Iran and the Middle East, employed stochastic and mathematical modeling to improve coordinated resource security and sustainability across interconnected water, energy, and food systems. Meanwhile, Melloni et al. (2020)[22] and van den Heuvel et al. (2020)[23], based on applications in European contexts, emphasized stakeholder-driven assessments and ecosystem services in evaluating nexus trade-offs.

Jin et al. (2020)[24] and Nhamo et al. (2020)[25] presented integrative frameworks addressing synergies and trade-offs in water–energy–food systems using system dynamics modeling and policy-oriented decision support tools. Sadegh et al. (2020)[26] and Slorach et al. (2020)[27] developed decision support tools and sustainability indicators targeting urban and food waste systems, while studies such as Wade et al. (2020)[28], Tan et al. (2020)[29], Zare et al. (2020)[30], and Wolde et al. (2020)[31] demonstrated applications of nexus approaches in regional planning and community-level resilience strategies.

Despite the growing body of literature employing Water–Energy–Food (WEF) or Water–Energy–Carbon (WEC) nexus perspectives, a significant research gap persists in studies that explicitly integrate water, energy, and carbon dimensions within the context of cotton production. While previous research has often focused on individual components such as water or energy footprints, comprehensive analyses incorporating the carbon dimension alongside land use dynamics remain limited. To address this gap, the present study adopts a holistic WEC nexus approach to analyze cotton production in Türkiye and to evaluate future scenarios under projected changes in precipitation (green water availability), land use, and renewable energy utilization. By integrating land-use trajectories, renewable energy targets, and water availability constraints into a unified, scenario-based assessment framework, this study provides novel insights into resource interdependencies and supports policy-relevant evaluations for sustainable agricultural planning in water-stressed regions. To the best of our knowledge, this represents the first WEC nexus-based modeling application focused on cotton production in Türkiye.

Materials and methods

Water, energy and carbon footprint approach to cotton production

This study applies a Water–Energy–Carbon (WEC) footprint-based framework to quantify resource use and emissions associated with cotton production in Türkiye. The methodological approach was structured in two sequential stages to ensure transparency and reproducibility.

In the first stage, the current (baseline) water use, energy consumption, and carbon emissions of cotton production were quantified. This assessment focused on the main production inputs and operations, including blue and green water use, energy consumption for tractor operations and cotton harvesting, energy requirements for unpressurized and pressurized irrigation systems, and energy inputs associated with fertilizer production according to Degirmencioglu et al. (2019)[32]. Carbon emissions were subsequently calculated based on the quantified energy inputs and corresponding emission factors. In this framework, water and energy are treated strictly as input variables, while carbon emissions are considered an output indicator derived from energy consumption[33]. The analysis therefore focuses on how variations in water and energy inputs indirectly influence carbon emissions through energy-related pathways, rather than treating carbon as an input variable.

In the second stage, future scenario analyses were conducted to evaluate the potential impacts of climate and policy-driven changes. These scenarios were defined by systematic variations in three key drivers:

(i) precipitation levels affecting green water availability,
(ii) cotton cultivation area (land-use change), and.
(iii) the share of renewable energy in the energy mix.

The combination of these drivers allowed the comparison of alternative future pathways relative to the baseline conditions, as summarized in Table 1.

The calculation of the WEC indicators followed a stepwise and reproducible procedure, as outlined below.

Step 1. Data collection: Water use, energy consumption, and production data were compiled at the provincial level for the baseline year 2021 from official national statistics[34]. Energy-related emission factors were obtained from[35,36].

Step 2. Calculation of water, energy, and carbon indicators: Blue and green water use were calculated based on irrigation requirements and precipitation-derived water availability. Energy consumption was estimated for major agricultural operations, including tractor use, irrigation, harvesting, and fertilizer application. Carbon emissions were calculated by multiplying energy consumption values by corresponding emission factors.

Step 3. Scenario adjustment: Future scenarios were implemented by modifying baseline values according to predefined assumptions on precipitation reduction, land-use change, and renewable energy penetration. All other parameters were held constant to ensure comparability across scenarios.

Codes	Explanation
TWR	Total water required for cotton production.
TBWR Until 2040	Total blue water required for cotton production until 2040.
TBWR 2041–2070	Total blue water required for cotton production between 2041 and 2070.
TGWR Until2040	Total green water required for cotton production until 2040.
TGWR 2041–2070	Total green water required for cotton production between 2041 and 2070.
TER	Total energy requirement for cotton production.
TRE Until 2040	The predicted renewable energy use (%15) in cotton production until 2040.
TRE 2041–2070	The predicted renewable energy use (%50) in cotton production between 2041 and 2070.
TCE Until2040	The predicted Carbon emission amount in cotton production until 2040.
TCE 2041–2070	The predicted Carbon emission amount in cotton production between 2041 and 2070.
Li_0^5	The actual size of cotton production land (L_0) and five different estimated sizes.

Table 1. Definitions of indicators and scenario-related codes used in the WEC analysis.

Scenario	Cultivation area (ha)	Precipitation change	Renewable energy share	Scenario description
L_0	518,000	Baseline (no reduction)	Baseline	Baseline cotton production conditions representing the actual situation in 2021
L_1	350,000	−20% until 2040; −36% until 2070	15% (2040); 50% (2070)	Contraction scenario reflecting reduced cultivation area under climate change and energy transition
L_2	400,000	−20% until 2040; −36% until 2070	15% (2040); 50% (2070)	Moderate contraction scenario allowing comparison across land-use pathways
L_3	450,000	−20% until 2040; −36% until 2070	15% (2040); 50% (2070)	Reference expansion pathway under combined climate and energy policy assumptions
L_4	500,000	−20% until 2040; −36% until 2070	15% (2040); 50% (2070)	Moderate expansion scenario representing gradual land-use growth
L_5	550,000	−20% until 2040; −36% until 2070	15% (2040); 50% (2070)	High expansion scenario reflecting intensified cotton production under future conditions

Table 2. Description of land-use, climate, and energy scenarios considered in the study.

Step 4. Normalization: To enable comparison and aggregation, all water, energy, and carbon indicators were normalized using a min–max scaling approach, with the baseline scenario (L_0, 2021) used as the reference point for defining relative changes across scenarios.

Step 5. Aggregation: The normalized water, energy, and carbon indicators were aggregated using equal weights to construct the composite WEC Index. Equal weighting was adopted to maintain transparency and avoid introducing subjective prioritization among nexus dimensions.

All scenarios incorporate a two-stage green water availability reduction: 20% for Until 2040, and an additional 20% (36% cumulative) for 2041–2070. Land size changes (L_1–L_5) represent possible variations from the 2021 baseline (L_0 = 518,000 ha) due to climate or policy shifts.

Future scenarios were constructed to examine the combined effects of climate change, land-use dynamics, and energy policy on cotton production (Table 2). In this context, Türkiye is expected to face an increase in irrigation water requirements over time due to projected reductions in monthly total precipitation associated with climate change. Climate-related changes were represented by projected reductions in precipitation, which directly affect green water availability. Precipitation data were considered on a monthly basis, consistent with the estimation of crop water requirements from the literature, allowing the identification of months in which irrigation is required or not required. Based on Türkiye's Seventh National Communication under the UNFCCC (Ministry of Environment and Urbanization, 2018, p. 130)[37], green water availability was reduced by 20% for the period 2021–2040 and by an additional 20% for the period 2041–2070. This reduction increases reliance on blue water for irrigation, thereby leading to higher energy demand and associated carbon emissions. Land-use scenarios (L_0–L_5) were defined as exploratory trajectories to reflect possible expansions or contractions of cotton cultivation area under future market and policy conditions. The baseline scenario (L_0) represents the actual cotton cultivation area in 2021 (518,000 ha). Alternative scenarios range from a contraction scenario (L_1: 350,000 ha) to an expansion scenario (L_5: 550,000 ha), with intermediate steps (L_2–L_4) introduced using consistent land-area increments. These stepwise changes were designed to enable systematic and comparable assessment of how variations in cultivation area influence water, energy, and carbon indicators, rather than to represent precise land-use forecasts.

Energy transition assumptions were incorporated into each scenario based on national energy policy targets, whereby renewable energy was assumed to account for 15% of the total energy mix used in cotton production by 2040 and 50% by 2070. These shares represent the proportion of renewable energy in the overall energy supply for agricultural operations, including electricity used for irrigation pumping and pressurized irrigation systems, and are aligned with Türkiye's national energy transition and decarbonization objectives as reported in official policy documents[37]. These climate, land-use, and energy policy assumptions collectively form the inputs of the

WEC Index framework, which translates scenario conditions into water, energy, and carbon indicators that are subsequently aggregated into sustainability scores, as illustrated in Fig. 1.

Figure 1 illustrates the conceptual structure of the WEC framework applied in this study and the key interactions considered among system components. Within the analytical framework, irrigation demand directly links water use to energy consumption through pumping and distribution processes, while energy policy assumptions, particularly renewable energy adoption, influence the emission intensity of irrigation-related energy use. Energy consumption constitutes the primary driver of carbon emissions, such that improvements in energy efficiency and shifts toward renewable energy sources reduce carbon outputs. Changes in water availability, driven by precipitation decline, affect irrigation requirements and indirectly modify energy demand and associated emissions. Land-use change operates as a scaling factor across all WEC dimensions, as expansion or contraction of cultivated area proportionally alters total water demand, energy consumption, production volume, and aggregate carbon emissions. These interactions are explicitly represented in the scenario calculations by linking climate, land-use, and energy assumptions to the corresponding water, energy, and carbon indicators used in the WEC Index.

Location

Data on cotton production were compiled for 22 provinces across different regions of Türkiye for the year 2021. Cotton production is spatially concentrated in a limited number of provinces, with Şanlıurfa representing the largest production area and output. Other major cotton-producing provinces include Aydın, Hatay, Diyarbakır, Adana, and İzmir. Together, these provinces account for a substantial share of national cotton production[34].

Figure 2 provides a descriptive overview of the study area. The map highlights the provinces included in the analysis to support spatial orientation of the case study, while the accompanying bar chart presents the relative contribution of each province to total national cotton lint production. The figure is intended solely for descriptive purposes and does not represent a spatially explicit analytical assessment.

Data

For each city, specific data were collected to provide the basis for analyses of water, energy, and carbon footprints (Table 3).

Water use in cotton production

Blue water (BW) and green water (GW) were considered to determine water use in cotton production. Blue water refers to rivers, lakes, groundwater, and aquifers, and is considered the main source of irrigation water. Rainfall is considered GW, as it is stored in the soil[44]. Therefore, BW requirements for cotton production in Türkiye were calculated for each city using Eq. 1[32].

$$Wi = Li\,(Ws - 10\,.\,Wa) \tag{1}$$

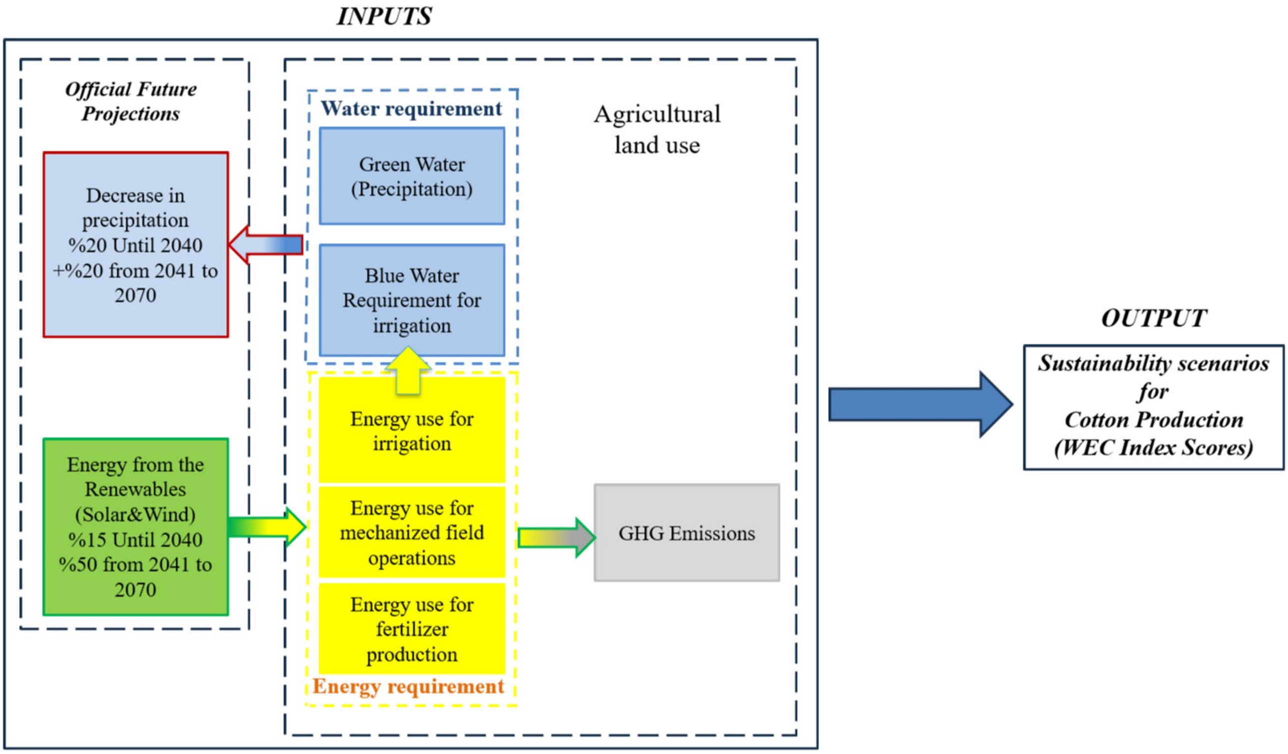

Fig. 1. Conceptual framework of the WEC Index approach applied to cotton production in Türkiye.

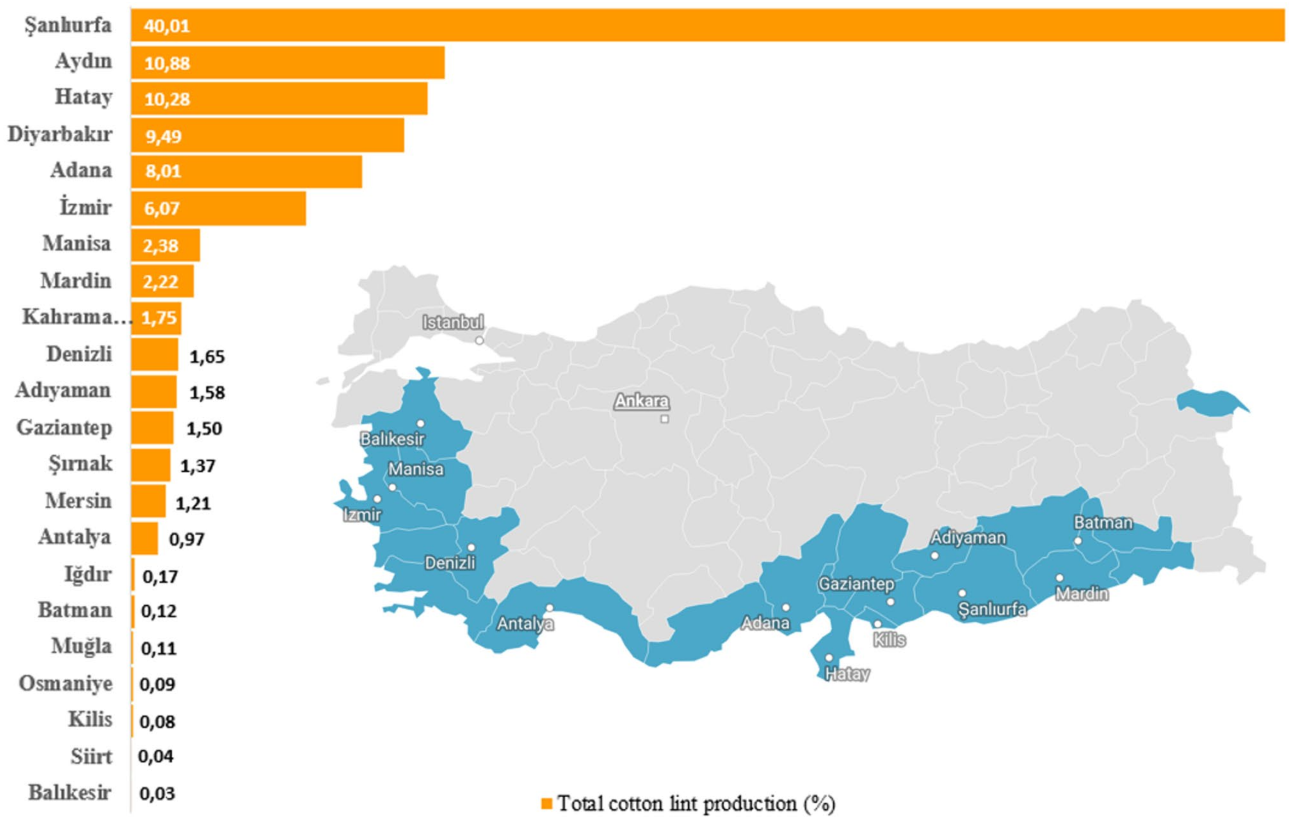

Fig. 2. Geographic distribution of cotton-producing provinces in Türkiye and their relative contribution to national lint production (2021).

Data	References
Cotton production area, yield of lint production, number of tractors and tractor power distribution of 22 cities for 2021	[34]
Water requirements of cotton for different cities in 2021	[38]
Water use for irrigation	[39]
Monthly precipitation data of production areas for cotton production period of Nov 2020-Nov 2021	[40]
Tractor use (hours) per hectare for cotton cultivation	[41]
Fertilizer requirements of cotton production in the cities	[42,43]

Table 3. The data for the water, energy and carbon footprint analyses.

where;

Wi Total blue water requirement of each city (m^3),

Li Land allocated for cotton production (ha).

Ws Seasonal water (green + blue) requirement of cotton depending on the city ($m^3\ ha^{-1}$).

Wa Seasonal water available by precipitation (Green water – mm).

The seasonal water requirement (*Ws*) and seasonal available water from precipitation (*Wa*) were calculated using province-specific data published by the General Directorate of State Hydraulic Works[36]. Monthly effective precipitation values were used to estimate *Wa*, while *Ws* was determined by calculating the monthly difference between crop evapotranspiration (ETc) and effective precipitation throughout the cotton growing season. The total irrigation requirement was then aggregated on an annual basis ($m^3\ ha^{-1}$). This method allowed the separation of blue and green water components and ensured regional climatic variability was appropriately considered in the water demand estimations.

Energy use in cotton production

As with most crops, the energy requirements of cotton production consist of energy used in agricultural operations and irrigation. Accordingly, the total energy requirement can be calculated according to Eq. 2[32].

$$E = E_1 + E_2 \tag{2}$$

where,

E Total energy needed for the cotton production (GJ).

E_1 Energy needed for irrigation (GJ).

E_2 Energy needed for agricultural operations (GJ).

Irrigation is required for all cotton production areas. Two types of irrigation were considered: unpressurized and pressurized. Unpressurized irrigation is applied to 65% of the cotton cultivation area, while pressurized irrigation accounts for 35%[39].

Thereof Eq. 3 has been used to determine the energy needed for irrigation[32];

$$E_1 = E_{GW} + E_{SW} \tag{3}$$

where,

E_{GW} Total energy needed for pumping water from deep well pumps (GJ).

E_{SW} Total energy needed for pumping surface water (GJ).

Regarding to the farming operations in cotton cultivation, fertilizer and diesel energy inputs have the highest share in energy consumption[16]. Accordingly, Eq. 4 has been used to determine energy needed for farming operations[32];

$$E_2 = E_d + E_f \tag{4}$$

where,

E_d Total energy equal to diesel input needed for tractor and cotton picker operations (GJ).

E_f Total energy needed for fertilizer production (GJ).

The energy required for tractor operations depends on the hourly diesel consumption of tractors (Eq. 5)[42] and the duration of tractor use per hectare, which is calculated as 31 h ha^{-1} based on the average usage[45,46].

$$Q_{avg} = 0.223.P_{pto} \tag{5}$$

where,

Q_{avg} average diesel consumption, (l h^{-1})

P_{pto} maximum PTO power, (hp)

The energy required for combine harvesting was estimated as 17 L ha^{-1} based on interviews with cotton experts consistent with literature[47].

As a result of energy consumption, carbon is released[48–51], and carbon footprints can be estimated through Eqs. 6, 7, and 8[32]. The emission factors used in this study were based on internationally recognized reports and databases. For fertilizer production emissions, the values reported in[37], as cited by the IEA Bioenergy Task, were used. Diesel and hydropower emissions were derived from Sovacool (2008)[36], while solar energy emissions were based on the IPCC AR5 Annex III parameters[52]. These emission factors were compiled and applied by Degirmencioglu et al. (2019)[32], which served as the basis for the carbon calculations in this study.

$$C = C_1 + C_2 \tag{6}$$

where,

C Total carbon emitted to the atmosphere (tons).

C_1 Total carbon emitted by irrigation operations (tons).

C_2 Total carbon emitted by agricultural operations (tons).

$$C_1 = C_{GW} + C_{SW} \tag{7}$$

where,

C_{GW}: Total carbon emitted by irrigation operations using ground water (tons).

C_{SW}: Total carbon emitted by irrigation operations using surface water (tons)

$$C_2 = C_d + C_f \tag{8}$$

where,

C_d Total carbon emitted by tractor and cotton picker operations (tons).

C_f Total carbon emitted by fertilizer production (tons).

To harmonize indicators across water, energy, and carbon metrics, all indicators were normalized to a common dimensionless scale using a min–max scaling approach prior to aggregation, following prevalent practices in simulation-based WEF nexus studies, as reviewed by Farmandeh et al. (2024)[53]. Regarding the interconnection analysis among water, energy, and carbon components, this study was conceptually informed by recent advances in composite WEF/WEC index modeling, such as the framework proposed by He et al. (2024)[54]. Recent studies by He et al. have proposed advanced composite index frameworks for the water–energy–food nexus, initially introduced in preprint form[55] and subsequently refined and published in a peer-reviewed journal[54]. The earlier work outlines the conceptual foundations of composite nexus indices, while the later publication advances the framework by incorporating governance dimensions, alternative weighting schemes, and robustness-oriented methodological enhancements. While such approaches provide substantial methodological depth, the present study deliberately adopts a parsimonious and transparent index structure to support scenario-based policy screening and interpretability under data constraints.While the study employs advanced techniques including governance integration, Principal Component Analysis (PCA), and uncertainty and sensitivity analysis, the present work adopts a simplified and deterministic formulation to prioritize transparency, reproducibility, and applicability in scenario-based assessments of cotton production.

The Water–Energy–Carbon (WEC) nexus composite index applied in this study was constructed through a transparent and deterministic procedure to enable consistent comparison across alternative land-use and energy scenarios. First, indicators representing water use (blue and green water), energy consumption, and carbon emissions were identified based on cotton production activities. All indicators were normalized to a common dimensionless scale using a min–max normalization approach to eliminate unit inconsistencies and allow direct comparison across nexus dimensions. For clarity, lower WEC Index values indicate improved sustainability performance, reflecting reduced water use, lower energy demand, and decreased carbon emissions, whereas higher values correspond to greater environmental pressure.

To ensure consistency among land-use scenarios (L_1–L_5), normalization was performed with reference to the baseline scenario L_0, which represents current land-use conditions in 2021 (518,000 ha). The baseline values were set as the reference point, and all alternative scenario outcomes were scaled within the [0–1] interval relative to this baseline. This approach enables direct comparison of water, energy, and carbon indicators across scenarios in terms of their deviation from present-day conditions. Min–max normalization is widely applied in sustainability assessment and life-cycle analysis studies; alternative approaches include z-score normalization and target-based normalization[56]. By using L_0 as a reference, relative changes in water demand, energy requirements, and carbon emissions under alternative land expansion pathways can be quantitatively assessed. This facilitates the identification of sustainability trade-offs and provides a clear basis for evaluating the impacts of future agricultural land-use strategies.

Following normalization, the water, energy, and carbon indicators were aggregated using equal weights to obtain the composite WEC Index. The equal weighting scheme was intentionally adopted to ensure transparency, simplicity, and reproducibility, and to avoid introducing subjective prioritization among the water, energy, and carbon dimensions. While alternative weighting approaches such as data-driven methods (e.g., PCA-based weights) or policy-driven weighting schemes could yield different index values and rankings, these were beyond the scope of the present study and are suggested as potential extensions for future research. The resulting index serves as a parsimonious and interpretable sustainability metric, allowing straightforward comparison of alternative scenarios, where lower index values indicate better alignment with sustainability objectives and reduced overall nexus pressure.

While advanced composite index methodologies in the literature incorporate techniques such as Principal Component Analysis (PCA) and uncertainty or sensitivity analysis to address multicollinearity and robustness, these methods were not implemented in the present study. This choice was intentional and reflects the objective of developing a transparent, reproducible, and policy-oriented screening tool suitable for scenario-based assessment of cotton production systems. The application of PCA and uncertainty analysis typically requires larger datasets and additional assumptions, which may limit interpretability and practical applicability in policy-relevant agricultural contexts. Future research may extend the proposed WEC index framework by integrating PCA-based weighting schemes and formal sensitivity or uncertainty analyses as more comprehensive datasets become available.

Results & discussion

Water and energy, the most basic and indispensable inputs of cotton production, along with the resulting carbon emissions, were determined for cotton-producing cities in Türkiye. Lint production, water requirements, total energy input, and total carbon emissions are presented in Table 4. Total cotton lint production in Türkiye was 977,440.62 tons, with Şanlıurfa contributing 40% of the total. The total energy requirement and total carbon emissions were calculated as 16.2 PJ and 660,173.39 tons (2,852.58 kg CO_2eq ha^{-1}), respectively. Energy productivity was calculated as 0.06 kg MJ^{-1}, which is identical to the results of a previous study in Türkiye[15]. However, it is lower than the 0.11 kg MJ^{-1} reported by Pishgar-Komleh et al. (2012)[57] in Iran and the 0.32 kg MJ^{-1} reported by Kargwal et al. (2022)[58]. Similarly, Abbas et al. (2022)[59] reported an energy productivity of 0.13 kg MJ^{-1}, which is higher than our findings, and total greenhouse gas (GHG) emissions of 1,106.12 kg CO_2eq ha^{-1}, which are lower than in this study. Such differences can be attributed to whether the focus is at the city, regional, or national scale, as well as to variations in farming systems across countries. Chapagain et al. (2006) reported blue, green, and total water requirements for cotton production in Türkiye as 6.20, 0.60, and 6.80 billion m^3, respectively, for the period 1997–2001[60]. In this study, the blue, green, and total water requirements for cotton production were calculated as approximately 4.12, 0.95, and 5.07 billion m^3, respectively. Water requirements may vary due to temporal changes in climate and differences in estimation methodologies, while more efficient water use can be achieved through increased adoption of modern irrigation technologies.

After establishing the current situation, future scenarios were developed with a focus on changes in rainfall, cultivated land area, and the share of renewable energy use. Land-based scenarios for total blue water requirement (TBWR), total green water requirement (TGWR), and total water requirement (TWR) were developed for the periods “up to 2040” and “2041–2070,” as shown in Fig. 3.

Figure 3 illustrates the relationship between cotton cultivation area and irrigation water requirements under different climate scenarios. While an increase in water demand with expanding land area is expected, the results indicate that this relationship becomes markedly more critical after 2040, when projected precipitation declines reduce green water availability. Under these conditions, additional land expansion leads to a disproportionate increase in irrigation demand, thereby amplifying pressure on blue water resources.

From a decision-making perspective, these findings suggest that cotton land expansion strategies that may appear feasible under current climate conditions could become unsustainable in the mid- to long-term. Policies promoting land expansion beyond 2040 should therefore be accompanied by parallel investments in irrigation

City	Total cotton lint production (tons)	Total blue water requirement (m^3)	Total green water requirement (m^3)	Total water requirement (m^3)	Total energy (GJ)	Total carbon emission (tons)
Adana	78309,29	216873222,60	79686951,40	296560174,00	1059478,69	43430,29
Adıyaman	15451,77	64304995,20	28005337,80	92310333,00	251177,96	10533,46
Antalya	9453,26	38106588,60	4930621,40	43037210,00	150475,18	5764,92
Aydın	106304,42	353113210,70	109686831,30	462800042,00	1543613,62	63540,80
Balıkesir	324,87	1192655,10	445071,90	1637727,00	5293,29	221,43
Batman	1133,77	3855354,60	600263,40	4455618,00	16140,14	692,24
Denizli	16128,42	46063111,00	41334359,00	87397470,00	225295,95	9517,92
Diyarbakır	92711,02	447414755,20	64657532,80	512072288,00	1547464,47	61933,69
Gaziantep	14633,16	47568912,00	17946048,00	65514960,00	209599,13	9098,54
Hatay	100476,56	396421279,80	35579380,20	432000660,00	1552014,84	59771,40
Iğdır	1624,41	6051166,70	1273264,30	7324431,00	25031,87	1123,37
Kahramanmaraş	17098,67	67722634,80	9689245,20	77411880,00	272954,68	10636,61
Kilis	787,97	4173926,40	572313,60	4746240,00	14137,16	559,05
Manisa	23297,92	67758966,80	24611633,20	92370600,00	283741,66	11456,37
Mardin	21671,62	103182783,00	18868325,00	122051108,00	356297,14	14270,26
Mersin	11800,82	32227715,20	16124300,80	48352016,00	149659,51	6021,35
Muğla	1086,30	3649968,00	2306577,00	5956545,00	16269,06	668,86
Osmaniye	839,54	2568364,40	1020771,60	3589136,00	13086,52	543,69
Siirt	381,81	1801958,40	331041,60	2133000,00	6845,28	284,47
İzmir	59370,88	231657390,00	27188532,00	258845922,00	814616,13	30911,53
Şanlıurfa	391117,21	1935220168,60	457769133,40	2392989302,00	7455312,52	311516,25
Şırnak	13436,95	47406509,60	7637846,40	55044356,00	183673,67	7676,89
Total	977440,62	4118335636,70	950265381,30	5068601018,00	16152178,46	660173,39

Table 4. The lint productions, water requirements, total energy input and total carbon emissions.

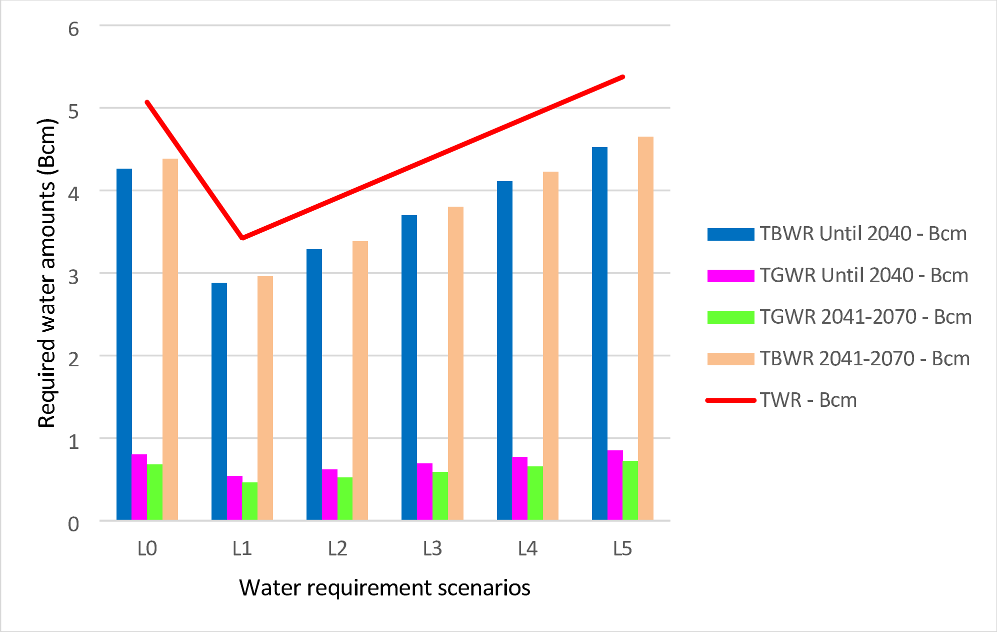

Fig. 3. Temporal total water requirement (in billion cubic meters, bcm) for cotton production under land size scenarios, where only the production area varies across the scenarios. L_0 (2021 baseline): 518,629 ha; L_1: 350,000 ha; L_2: 400,000 ha; L_3: 450,000 ha; L_4: 500,000 ha; L_5: 550,000 ha.

efficiency, water-saving technologies, or alternative production strategies to avoid exacerbating water scarcity risks.

The analysis of energy requirements and carbon emissions for cotton production under different land size scenarios (L_1–L_5) highlights key trends in resource use and environmental impacts (Fig. 4). The total energy requirement (TER) increases consistently with expanding land area, with the L_5 scenario exhibiting the highest energy demand. This pattern reflects a monotonic relationship between cultivated area and energy use, as larger production areas require greater energy inputs for irrigation, mechanized field operations, and harvesting activities.

The projected renewable energy use (TRE) was estimated by applying Türkiye's national renewable energy targets; 15% by 2040 and 50% by 2041–2070[61] to the total energy demand of cotton production. These targets represent the assumed share of renewable energy in the overall energy mix used for agricultural operations and were incorporated to reflect national energy transition pathways. Accordingly, renewable energy use increases over time across all scenarios, consistent with policy-driven decarbonization objectives.

Despite this increase in renewable energy adoption, total carbon emissions (TCE) are projected to rise with expanding land areas, particularly under the 2041–2070 scenarios (Fig. 5). This indicates that while higher renewable energy penetration reduces the carbon intensity of energy use, it does not fully offset the absolute increase in emissions associated with larger-scale cotton production. The results therefore highlight that land expansion remains a dominant driver of energy demand and emissions, underscoring the need for coordinated land-use planning and energy transition strategies to effectively manage future carbon impacts.

In terms of sustainable energy production, cotton also has the potential to contribute through the utilization of agricultural residues for energy generation[62]. This potential could be explored in future studies, which may also encompass renewable, carbon-neutral energy sources. These findings highlight the need for more aggressive renewable energy integration and carbon reduction strategies to meet sustainability goals and manage the environmental impacts of future cotton production in Türkiye.

Normalizing multidimensional sustainability indicators is a widely adopted strategy to ensure comparability and aggregation, especially in simulation-based Water-Energy-Food and additive input/output Nexus studies[53]. To further evaluate the interdependencies among water, energy, and carbon components under varying cotton land use scenarios, a WEC Nexus Index was developed. This composite indicator integrates three normalized variables—total water requirement (TWR), total energy requirement (TER), and total carbon emissions (TCE)—corresponding to both the up to 2040 and the 2041–2070 periods. All values were normalized using min–max scaling, with the baseline year (L_0, 2021) set to 1.0, enabling relative comparison across scenarios. The WEC Index was then calculated as the arithmetic mean of the normalized components. As defined in

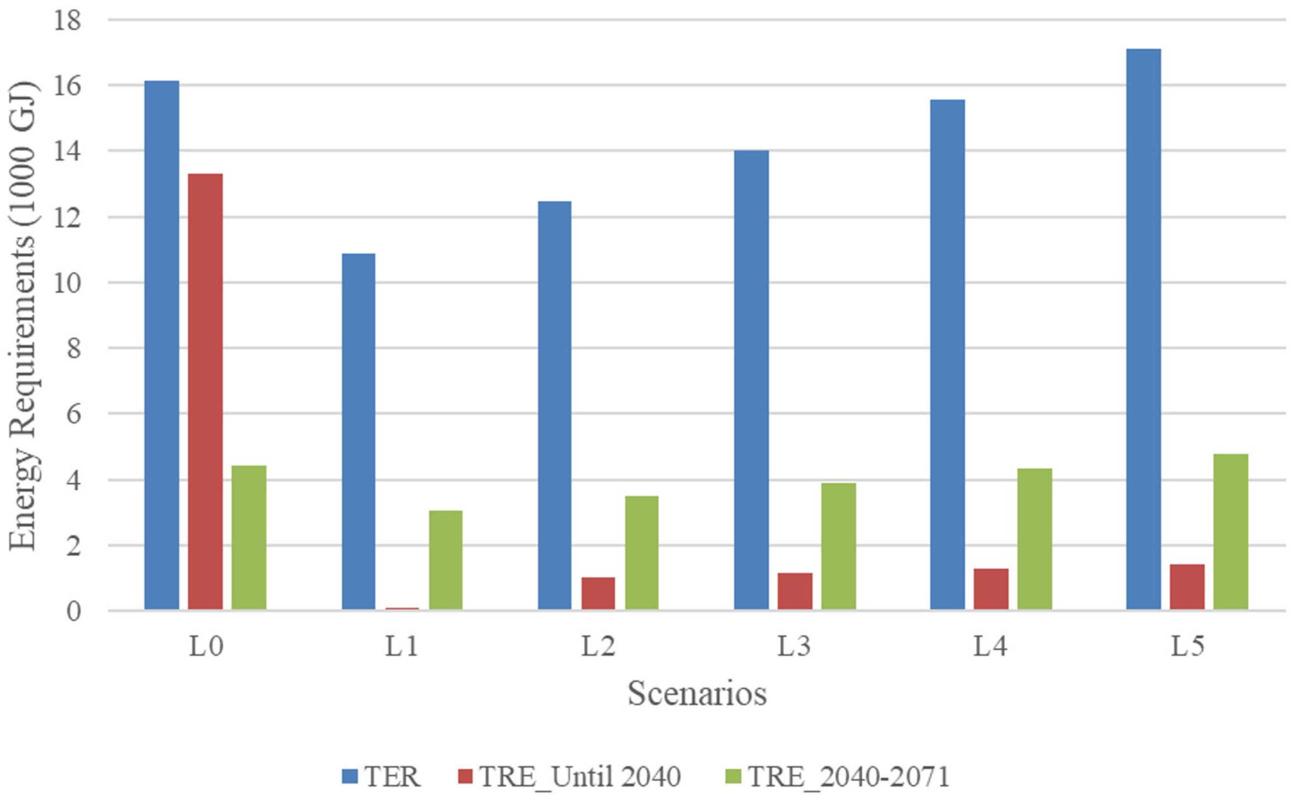

Fig. 4. Total energy requirement (TER-GJ), The predicted renewable energy use in cotton production until 2040 (TRE_Until 2040-GJ) and the predicted renewable energy use in cotton production between 2041 and 2070 (TRE_2041-2070-GJ).

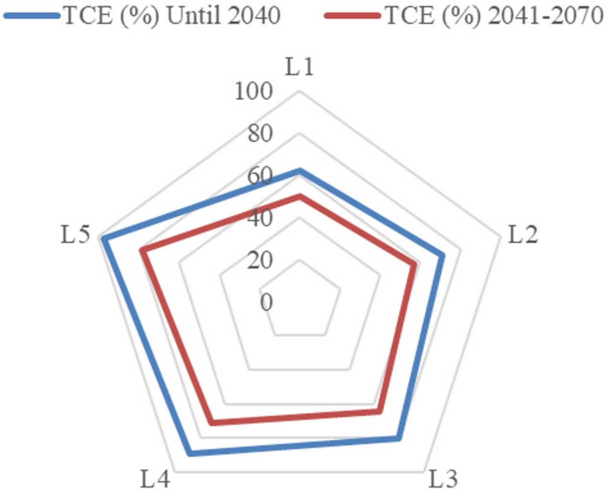

Fig. 5. Percentage change in carbon emissions (TCE) in cotton production until 2040 and between 2041–2070. Since Fig. 5 presents percentage changes relative to the baseline (L_0), the L_0 scenario corresponds to the center of the chart rather than being displayed as a separate series.

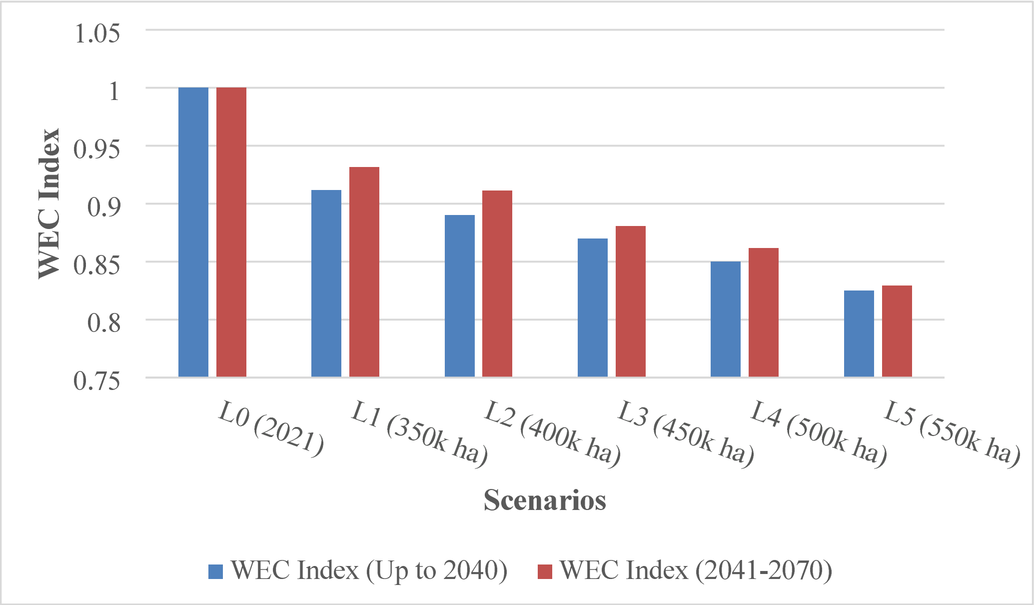

Fig. 6. Comparison of normalized WEC index values across cotton production scenarios for two time periods (Up to 2040 and 2041–2070).

the methodological framework, lower index values represent more sustainable outcomes in terms of reduced resource use and emissions. For clarity, throughout this manuscript, lower WEC Index values consistently indicate improved sustainability performance, whereas higher values reflect greater combined pressure on water, energy, and carbon resources.

As shown in Fig. 6, the WEC Index exhibits a consistent downward trend with the expansion of cotton cultivation area, indicating increasing environmental pressure. This trend becomes more pronounced beyond the L_3 scenario (450,000 ha), where water consumption, energy demand, and carbon emissions escalate significantly, leading to lower WEC scores. Notably, although the 2041–2070 period benefits from a higher share of renewable energy in the national portfolio (50% compared to 15% up to 2040), the WEC Index values remain consistently lower for the earlier period. This outcome suggests that land use change exerts a dominant influence on sustainability outcomes, partially offsetting the gains from increased renewable energy integration.

This approach provides a practical and interpretable tool for quantifying integrated sustainability performance across land use scenarios. While more complex composite index formulations exist, the WEC Index applied here prioritizes transparency, reproducibility, and interpretability to support policy-oriented scenario comparisons. In line with the framework proposed by He et al. (2024)[54], the WEC Index may be further refined through advanced techniques such as Principal Component Analysis (PCA) or quasi–Monte Carlo simulation to account for uncertainty and latent interdependencies. Although the current methodology relies on equal weighting and simple averaging, its extension through multi-criteria decision-making frameworks and governance-related indicators. He et al. highlights the potential of the methodology that could significantly enhance its utility for agricultural policy design and long-term planning. In the interpretation of the WEC Index, lower values consistently represent more sustainable outcomes, while increasing index values indicate rising pressure on water, energy, and carbon systems.

These findings emphasize the necessity for the formulation of targeted water and energy management policies to address the environmental challenges associated with the expansion of cotton production areas.

Nexus trade-offs and synergies

Beyond individual indicator trends, the WEC nexus framework applied in this study allows the identification of key trade-offs and synergies emerging from alternative cotton production pathways. A primary trade-off is observed between land expansion and water sustainability, as increasing cultivation area substantially amplifies irrigation demand under declining precipitation conditions. This water–land trade-off becomes more pronounced after 2040, when reduced green water availability increases reliance on blue water resources, leading to higher energy consumption for irrigation and associated carbon emissions.

At the same time, important synergies emerge through energy transition pathways. Increased adoption of renewable energy reduces the carbon intensity of irrigation-related energy use, partially offsetting the emission impacts of higher water demand. This energy–carbon synergy improves overall WEC performance under scenarios that combine moderate land expansion with accelerated renewable energy penetration. The results therefore highlight that while land expansion alone tends to exacerbate nexus trade-offs, coordinated land-use planning and energy policy interventions can transform parts of the nexus into synergistic outcomes, supporting more balanced and resilient cotton production systems.

The scenario outcomes derived from the WEC framework have direct implications for agricultural policy and planning in Türkiye. In particular, the increasing total energy requirement and carbon emissions observed under larger land-use scenarios suggest the necessity of defining practical upper limits for cotton cultivation expansion in water- and energy-constrained regions. Recent national assessments of the cotton sector emphasize the growing pressure of irrigation demand, energy costs, and climate-related risks on production sustainability[63]. In addition, empirical evidence from Türkiye indicates that changes in land structure, such as land consolidation and increasing parcel size, can significantly influence agricultural mechanization levels and energy use patterns by enabling the adoption of more powerful machinery[64]. Within this context, the WEC Index results highlight that policy efforts should prioritize irrigation efficiency improvements, modernization of on-farm energy systems, and accelerated integration of renewable energy sources in agricultural production. Such measures would allow productivity gains while mitigating the water, energy, and carbon trade-offs identified in the higher land-area scenarios. These findings provide an evidence-based reference for defining region-specific cultivation thresholds and prioritizing efficiency-oriented investments in irrigated agriculture under future climate constraints.

Conclusions

This study presents the results of a comprehensive analysis of cotton production in Türkiye, with a particular focus on the interdependence of water, energy, and carbon emissions in the context of sustainable resource management. The findings indicate that as cotton production areas expand, water requirements will increase, particularly for blue and green water. Projections for 2041–2070 indicate a significant rise in water demand compared to the period up to 2040. These trends underscore the necessity for effective water management strategies and the prospective advantages of contemporary irrigation technologies to alleviate mounting demands, particularly in the context of climate variability.

Furthermore, the analysis shows that energy demand increases as production expands, demonstrating a consistent increase in energy use with larger land areas. Despite the renewable energy targets set by Türkiye (15% by 2040 and 50% by 2041–2070), total carbon emissions are projected to increase, particularly in scenarios involving larger land areas. This indicates that while the adoption of renewable energy is a crucial step, it may not be sufficient on its own to offset the environmental consequences of increased production. Additional measures, such as improving energy productivity and integrating advanced carbon reduction strategies, are therefore imperative to align cotton production with Türkiye's sustainability goals.

The study has several limitations. Region-specific emission factors and high-resolution crop management data were not available, which may have affected the granularity of energy and carbon estimates. Furthermore, precipitation reduction assumptions were applied uniformly across regions based on general climate trends, which introduces uncertainty into green water availability projections.

Future research could improve the methodology by integrating spatially explicit climate models, detailed agricultural input data, and economic constraints. Moreover, behavioral factors affecting farmer responses to climate and policy shifts could enhance scenario realism.

Despite these limitations, the holistic WEC nexus-based approach presented here offers a replicable framework applicable to other regions facing similar water stress, agricultural intensification, and sustainability trade-offs. By adjusting the model inputs and assumptions, this approach can guide integrated planning in diverse agroecological and policy contexts worldwide.

Taken together, these results provide a foundation for rethinking sustainable cotton production policies in Türkiye amid mounting climate and land use pressures.

Data availability

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

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Author contributions

OE, AD, and GOE designed the study and wrote the manuscript. OE and GOE contributed to data collection. OE and AD performed the statistical analysis and interpretation of the results. GOE contributed to the visualization of data. SK revised the design of the study, conducted additional statistics and provided funding. All authors read, reviewed and approved the final manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

Correspondence and requests for materials should be addressed to Ö.E.

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