

Effects of irrigation technology on energy efficiency, carbon footprint, and water scarcity footprint in silage maize production: A three-year field study

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ARTICLE INFO

Keywords:

Sustainable water management
Agricultural resource productivity
Environmental footprinting
Pressurized irrigation
Agroecosystem sustainability

ABSTRACT

Efficient use of water and energy resources is increasingly important for sustaining agricultural production under growing food demand and climate change pressures. This study evaluated the effects of irrigation technology on energy performance, input-related carbon footprint, and water scarcity footprint in irrigated silage maize production. Field-based data were collected over three consecutive growing seasons (2022–2024) from a large commercial farm in Ankara Province, Central Anatolia, Türkiye, where silage maize was produced under sprinkler and center pivot irrigation systems. Energy performance was quantified using an input–output energy analysis framework, input-related carbon footprint was estimated using emission factors associated with agricultural inputs and field operations, and water scarcity footprint was assessed using the AWARE characterization factor for Türkiye. Based on three-year mean values, center pivot irrigation increased dry matter yield by 1.48%, energy use efficiency by 16.89%, energy productivity by 16.88%, and net energy by 3.27%, while reducing specific energy by 14.38% compared with sprinkler irrigation. The input-related carbon footprint per unit of dry matter yield decreased by 22.22% under center pivot irrigation. In contrast, the mean water scarcity footprint was identical between the two systems, and its pattern varied by year: sprinkler irrigation showed lower values in 2022 and 2023, whereas center pivot irrigation showed a lower value in 2024. Overall, center pivot irrigation improved energy performance and reduced input-related carbon footprint under the evaluated commercial farm conditions, while water scarcity footprint was mainly governed by irrigation water volume and the regional AWARE factor rather than irrigation technology alone. These findings provide field-based evidence for irrigation planning and resource-use assessment in semi-arid silage maize production systems.

1. Introduction

The repercussions of global climate change have become a matter of mounting concern for agricultural production and food security [1]. Drought, rising temperatures, erratic precipitation [2–4], diminishing water resources, and increasing energy consumption pose significant threats to agricultural sustainability. These impacts not only compromise crop productivity but also threaten human

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<https://doi.org/10.1016/j.wri.2026.100378>

Received 20 April 2026; Received in revised form 11 June 2026; Accepted 11 June 2026

Available online 11 June 2026

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health, agroecosystem functions, and food security [5–7]. In addition, with population growth continuing due to rapid urbanization and the world population expected to reach 9.7 billion by 2050 [8], there is a risk that sufficient feed and food will not be available. Indeed, according to Ref. [9] estimates, global food production should increase by approximately 60% in the coming years.

The agricultural sector is one of the largest users of water, with agricultural irrigation water accounting for about 70% of global freshwater consumption [10,11]. This suggests that agricultural water scarcity can severely constrain sustainable economic and social development, especially in regions with dwindling water resources [12,13]. Indeed, since the 1960s, the proportion of area affected by drought, as defined by the Palmer Drought Severity Index, has increased from 5–10% to 15–25% in all areas where staple crops such as barley, maize, rice, sorghum, soybean and wheat are grown globally [14]. These changes underscore the urgent need for improved water management in agriculture to ensure long-term sustainability.

As a finite and essential resource, water must be managed, conserved, and used efficiently to support the sustainability of agroecosystems [15]. In regions facing water stress, irrigation plays a crucial role in sustaining agricultural productivity [16,17]. Efficient irrigation practices are central to optimizing water use, improving agricultural productivity, and minimizing environmental impacts.

In agricultural production systems, optimizing the use of agricultural inputs is essential for reducing environmental burdens and improving water and energy productivity. This can be addressed through resource-use and environmental performance assessments, which aim to maximize production output while minimizing input consumption and associated environmental impacts [18]. In irrigated crop production, energy use efficiency (EUE), input-related carbon footprint, and water scarcity footprint (WSF) are particularly relevant indicators because they jointly reflect the energy demand, greenhouse gas implications, and water-related environmental pressure of production systems [19].

Recent studies have increasingly conceptualized agricultural sustainability through the water–energy–food–carbon nexus, recognizing that water use, energy demand, crop production, and carbon emissions are tightly interconnected within irrigated agroecosystems. In this context [20], developed an optimal allocation model for soil and water resources based on the water–energy–food–carbon nexus, integrating water allocation, crop production, economic returns, ecological benefits, and carbon constraints within a unified decision-making framework. Similarly [21], and [22] proposed multi-objective nexus-based optimization models for irrigation areas, emphasizing the need to simultaneously balance water resource allocation, energy consumption, agricultural productivity, carbon emission reduction, and economic performance. These studies demonstrate that single-dimensional assessments are insufficient for evaluating the sustainability of irrigated agricultural systems. Therefore, the combined assessment of energy use efficiency, input-related carbon footprint, and water scarcity footprint in the present study provides a field-based contribution to the water–energy–carbon dimension of the nexus framework and offers practical insight into how irrigation technology shapes resource-use and environmental performance under semi-arid conditions.

Maize (*Zea mays* L.) is one of the most widely cultivated crops worldwide and plays a major role in both food and feed production [23]. Maize production requires substantial water and energy inputs, particularly under irrigated conditions where pumping, water delivery, fertilization, field operations, and harvesting contribute considerably to total resource demand [24–27]. However, the environmental performance of irrigation practices may vary substantially depending on geographical location, climatic conditions, energy sources, irrigation infrastructure, and farm-level management [28]. Despite the increasing interest in the water–energy–carbon nexus, field-based evidence comparing sprinkler and center pivot irrigation systems using multi-year commercial farm data remains

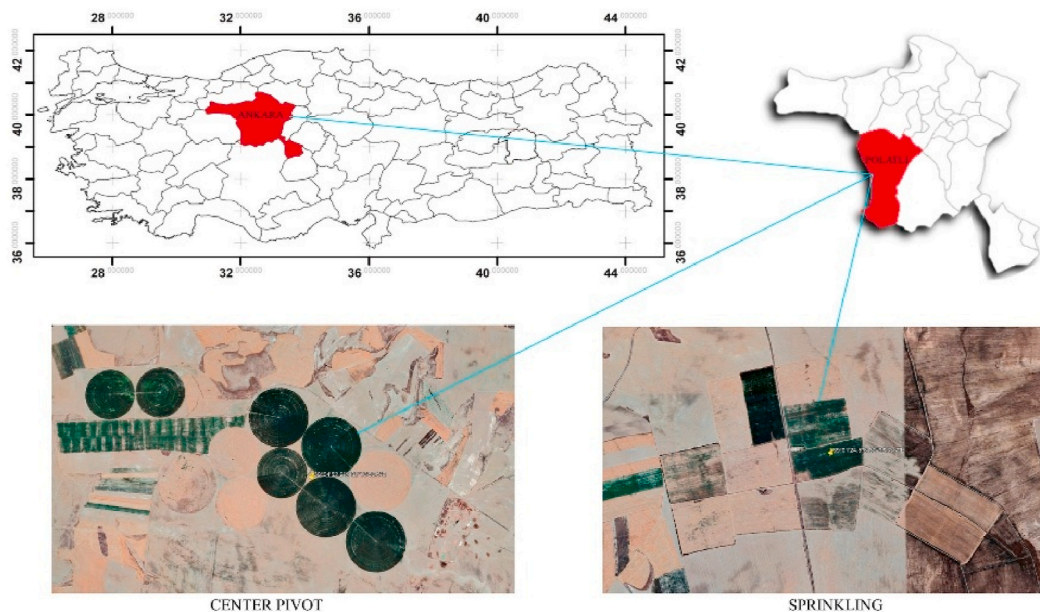


Fig. 1. Location of the study area.

limited, particularly for silage maize production under semi-arid conditions. Accordingly, this study evaluates the energy efficiency, input-related carbon footprint, and water scarcity footprint of silage maize production under sprinkler and center pivot irrigation systems in Ankara Province, Central Anatolia, Türkiye. By using three-year field-based data from a large commercial farm, the study aims to provide practical evidence on how irrigation technology shapes the water–energy–carbon performance of irrigated silage maize production under semi-arid conditions.

2. Materials and methods

2.1. Study area Description

Field experiments were conducted over three consecutive growing seasons (2022–2024) at the Polatlı Agricultural Enterprise Directorate of the Ministry of Agriculture and Forestry, located in Polatlı district, Ankara province, Türkiye (coordinates: 39°04'52.9" N, 32°03'50.5" E; 39°01'24.5" N, 32°06'33.7" E; elevation: 850 m above sea level) (Fig. 1). The enterprise spans 21,134 ha, with center pivot irrigation used for maize cultivation on 206–217 ha, and sprinkler irrigation employed on 49–56 ha. The soil at the study site is clayey-loamy, with an electrical conductivity of 0.867 dS m^{-1} , indicating non-saline conditions. The pH of the soil is slightly alkaline at 7.91, and lime content is high at 18.39%. Organic matter content is 1.82%, which is considered insufficient, and phosphorus levels are low (57.3 kg ha^{-1}), while potassium is adequate ($1002.8 \text{ kg ha}^{-1}$). This study was designed as a real-world farm case study based on operational data collected from a large-scale commercial production system.

The study area lies in the Central Anatolia Region, characterized by a continental climate with hot, dry summers and cold, snowy winters. Climate data for the study area were obtained from the Turkish State Meteorological Service [29]. The climatic conditions during the maize growing seasons (April–September) of 2022–2024 were characterised by moderate temperatures and highly variable precipitation patterns (Fig. 2). The mean monthly air temperatures ranged from 11.0 to 28.8°C across the study years, with temperatures gradually increasing from April and peaking during July–August before declining toward September. Precipitation exhibited considerable intra-seasonal variability. Rainfall was found to be higher in spring, particularly in May 2023 (86.6 mm) and May 2024 (46.0 mm), whereas markedly lower precipitation was recorded during the mid-summer months. In the observed period, July exhibited a marked scarcity of rainfall, with figures of 0.4 mm, 1.0 mm and 5.6 mm recorded in 2022, 2023 and 2024, respectively. This indicates that the predominant weather conditions during this period were dry. It is evident that, on the whole, these climatic patterns are consistent with the semi-arid characteristics of the region.

2.2. Cultural practices

The maize variety used in this study was 72MAY80, which belongs to the FAO 700 maturity group. This variety is characterized by high adaptability, drought tolerance, and the ability to grow under varying soil conditions. Seeds were sown in the last week of April at a row spacing of $70 \times 14 \text{ cm}$ and a planting depth of 6 cm. The seeding rate was 32 kg ha^{-1} , and 166 kg ha^{-1} of DAP fertilizer (18-46-0) was applied as basal fertilizer. A second fertilization was performed at the V6 growth stage using 206 kg ha^{-1} of urea (46% N). In addition, herbicide was applied at a rate of 0.8 kg ha^{-1} for weed control. The study area was irrigated using sprinkler and center pivot irrigation systems (Fig. 3). Harvesting was carried out in the first week of September.

The study was conducted under real commercial farm conditions and was therefore evaluated as a field-based comparative case study rather than a strictly randomized controlled experiment. The sprinkler and center pivot irrigation systems were located within the same farming enterprise and were evaluated during the same growing seasons. In both irrigation areas, silage maize was cultivated, and key agronomic practices, including seeding rate, nitrogen and phosphate fertilization, herbicide application, and major field operations, were kept consistent according to the farm management protocol. These identical input rates were verified using farm input records and application logs and represented actual farm operations rather than estimated values. Therefore, the comparison reflects the practical effects of irrigation technology and its associated operational requirements under real field conditions.

In this farm-scale study, irrigation water use was evaluated based on the total seasonal irrigation water volume recorded for each

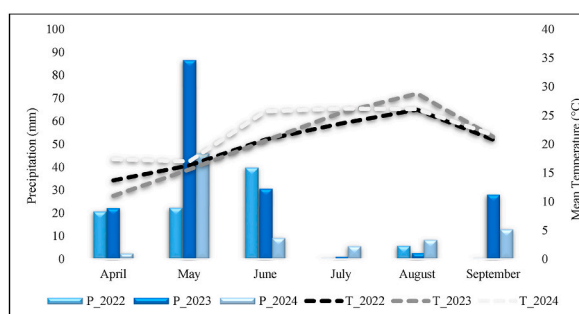


Fig. 2. Monthly precipitation (P, mm) and mean temperature (T, °C) recorded during the maize growing seasons (April–September) in the study area across 2022–2024.



Fig. 3. Schematic diagrams of sprinkler (a) and center pivot (b) irrigation systems.

irrigation technology. Therefore, the analysis focused on the actual water input used in silage maize production rather than on a detailed hydraulic performance assessment of the irrigation systems. Detailed operational parameters such as pump head, operating pressure, discharge rate, and event-based irrigation depths were not continuously recorded under farm conditions and were therefore not included in the analysis.

2.3. Assessment of energy, carbon, and water scarcity footprints

The application rates of agricultural inputs such as seeds, irrigation water, diesel fuel, herbicides, electricity, human labour, machinery, and chemical fertilizers were recorded during the experiment (Tables 1 and 2). The energy use efficiency (EUE) of irrigation systems was determined by input-output energy analysis, which estimates the efficiency of energy transformation throughout the maize production process. Carbon footprint (CF) was calculated by evaluating the greenhouse gas emissions associated with input use, and water scarcity footprint (WSF) was assessed by the volume of irrigation water consumed throughout the growing season. These indicators allowed for a comprehensive analysis of the environmental performance of maize production systems.

All input and output data used in the energy, carbon footprint, and water scarcity footprint calculations were obtained from farm records and field measurements during the 2022–2024 growing seasons. Electricity consumption was recorded from electricity meters and farm electricity bills for each irrigation system and was standardized on a per-hectare basis. Diesel fuel consumption was obtained from farm fuel records and machinery operation logs. Irrigation water volume was determined from the irrigation management records of the farm and expressed as $\text{m}^3 \text{ ha}^{-1}$ for each growing season. Human labour and machinery use were recorded based on field operation logs, including the duration of each operation, and were converted to h ha^{-1} . Fertilizer, seed, and herbicide application rates were obtained from farm input records and cross-checked with purchase and application records. Maize yield was measured at harvest as fresh biomass yield and then converted to dry matter yield using the measured dry matter content. Before analysis, all input data were checked for unit consistency, converted to a hectare basis, and reviewed for possible transcription or calculation errors.

Table 1
Agricultural inputs for maize production under sprinkler irrigation during 2022–2024.

Inputs	Unit	Years		
		2022	2023	2024
Human labour	h ha^{-1}	132.30	132.40	151.80
Machinery	h ha^{-1}	37.10	39.10	39.70
Diesel fuel	L ha^{-1}	340.00	340.00	340.00
Nitrogen (N)	kg ha^{-1}	124.00	124.00	124.00
Phosphate (P_2O_5)	kg ha^{-1}	76.00	76.00	76.00
Herbicides	kg ha^{-1}	0.80	0.80	0.80
Electricity	kWh ha^{-1}	1230.00	1230.00	1230.00
Irrigation water	$\text{m}^3 \text{ ha}^{-1}$	4700.00	4950.00	5700.00
Seed	kg ha^{-1}	32.00	32.00	32.00
Fresh biomass yield of silage maize	kg ha^{-1}	49,555.00	50,018.00	50,023.00
Dry matter yield of silage maize ^a	kg ha^{-1}	16,353.15	16,505.94	16,507.59
Area	ha	56.70	51.00	49.30

^a Dry matter yield was calculated from fresh biomass yield of silage maize using the measured dry matter content of 33%.

Table 2

Agricultural inputs for maize production under center pivot irrigation during 2022–2024.

Inputs	Unit	Years		
		2022	2023	2024
Human labour	h ha ⁻¹	31.40	31.40	38.60
Machinery	h ha ⁻¹	14.80	14.80	6.80
Diesel fuel	L ha ⁻¹	350.40	350.40	350.40
Nitrogen (N)	kg ha ⁻¹	124.00	124.00	124.00
Phosphate (P ₂ O ₅)	kg ha ⁻¹	76.00	76.00	76.00
Herbicides	kg ha ⁻¹	0.80	0.80	0.80
Electricity	kWh ha ⁻¹	450.00	450.00	450.00
Irrigation water	m ³ ha ⁻¹	5110.00	5218.00	5220.00
Seed	kg ha ⁻¹	32.00	32.00	32.00
Fresh biomass yield of silage maize	kg ha ⁻¹	51,550.00	50,023.00	50,240.00
Dry matter yield of silage maize	kg ha ⁻¹	17,011.50	16,507.59	16,579.20
Area	ha	217.50	217.50	206.70

* Dry matter yield was calculated from fresh biomass yield of silage maize using the measured dry matter content of 33%.

2.4. Energy input and output calculations

The agricultural energy input (AEI) (MJ ha⁻¹) associated with the inputs to grow 1 ha of maize was calculated using the following equation [30]:

$$AEI = \sum_i^n R(i) \times E_{eq}(i) \quad (1)$$

where $R(i)$ is the application rate of input i (unit_{input}ha⁻¹) and $E_{eq}(i)$ (Table 2) is the energy equivalent of input i (MJ unit_{input}⁻¹). Table 3 lists energy equivalent of agricultural inputs.

The yield values reported in Tables 1 and 2 represent the fresh biomass yield of silage maize measured at harvest. Fresh biomass samples were dried to determine dry matter content, which was measured as 33%. Accordingly, fresh biomass yield was converted to dry matter yield before calculating agricultural energy output (AEO). AEO was calculated by multiplying dry matter yield by the silage maize energy equivalent of 17.93 MJ kg⁻¹ [39].

The agricultural energy output (AEO) (MJ ha⁻¹) associated with the inputs to growing 1 ha of maize was calculated as following adapted [40]:

$$AEO = \sum_i^n Y(i) \times E_{eq}(i) \quad (2)$$

where $Y(i)$ is the yield rate of output i (unit_{input}ha⁻¹) and $E_{eq}(i)$ is the energy equivalent (often used lower heating values) of output i (MJ unit_{input}⁻¹). Table 3 lists energy equivalent of agricultural inputs.

Energy use efficiency (EUE), specific energy (SE), energy productivity (EP), and net energy (NE) in maize production were computed using the following formulas 3-6 [41–44].

$$EUE \text{ (decimal)} = \frac{AEO}{AEI} \quad (3)$$

$$SE \text{ (MJ kg}^{-1}\text{)} = \frac{AEI}{Y} \quad (4)$$

Table 3

Energy equivalents of inputs and output in maize production.

Inputs and output	Unit	Energy equivalent (MJ unit ⁻¹)	References
Human labour	h	1.96	[31]
Machinery	h	62.70	[32]
Diesel fuel	L	35.69	[33]
Nitrogen (N)	kg	45.00	[34]
Phosphate (P ₂ O ₅)	kg	8.00	
Herbicides	kg	269.00	[35]
Electricity	kWh	3.60	[36]
Irrigation water	m ³	1.14	[37]
Maize Seed	kg	16.60	[38]
Output	Unit	Energy equivalent (MJ unit ⁻¹)	References
Silage Maize	kg	17.93	[39]

$$EP \text{ (kg MJ}^{-1}\text{)} = \frac{Y}{AEI} \quad (5)$$

$$NE \text{ (MJ ha}^{-1}\text{)} = AEO - AEI \quad (6)$$

AEO: Agricultural energy output, AEI: Agricultural energy input, Y: Yield.

2.5. Carbon footprint (CF) calculation

The carbon footprint ($\text{kgCO}_{2\text{-eq}} \text{ ha}^{-1}$) associated with maize production was calculated using the following equation [45]:

$$CF_{\text{ha}} = \sum_{i=1}^n R(i) \times EF(i) \quad (7)$$

where $R(i)$ is the application rate of input i ($\text{unit}_{\text{input}} \text{ ha}^{-1}$) and $EF(i)$ is the CF coefficient of input i ($\text{kgCO}_{2\text{-eq}} \text{ unit}_{\text{input}}^{-1}$). Table 4 lists CF coefficients of agricultural inputs.

Moreover, CF_{kg} is defined to evaluate the amount of emitted $\text{kg CO}_{2\text{-eq}} \text{ kg}^{-1}$ yield as following adapted [53,54]:

$$CF_{\text{kg}} = \frac{CF_{\text{ha}}}{Y} \quad (8)$$

Carbon footprint (CF) was calculated by multiplying each agricultural input by its corresponding emission coefficient. Electricity consumption was recorded as kWh ha^{-1} and directly multiplied by the corresponding year-specific national electricity emission factor for Türkiye. Therefore, no kWh-to-MJ conversion was required for electricity-related carbon footprint calculations. Machinery use was recorded as working time (h ha^{-1}), converted into machinery energy input using the machinery energy equivalent of 62.70 MJ h^{-1} , and then multiplied by the machinery emission coefficient expressed as $\text{kg CO}_{2\text{-eq}} \text{ MJ}^{-1}$. For the remaining inputs, the recorded input quantities were directly multiplied by their respective emission coefficients according to their original units. Direct soil-derived N_2O emissions from nitrogen fertilizer application were not included in the carbon footprint calculation; therefore, the CF assessment represents input-related emissions within the farm-gate production boundary.

2.6. Water scarcity footprint (WSF) calculation

The water scarcity footprint ($\text{m}^3_{\text{world-eq}} \text{ ha}^{-1}$) was calculated based on the AWARE methodology, which characterizes water consumption in terms of regional water scarcity. The AWARE characterization factor for each agricultural input was applied to calculate the overall water scarcity footprint [19]:

$$WSF = \sum_{i=1}^n R(i) \times \text{AWARE}(i) \quad (9)$$

where $R(i)$ is the application rate of input i ($\text{unit}_{\text{input}} \text{ ha}^{-1}$) and $\text{AWARE}(i)$ is the AWARE characterization factor of input i ($\text{m}^3_{\text{world-eq}} \text{ unit}_{\text{input}}^{-1}$).

Table 5 lists AWARE characterization factor of agricultural inputs.

2.7. Comparative analysis

Because the dataset represents a single large-scale commercial farm and annual values were derived from operational farm records

Table 4
Carbon footprint (CF) coefficients of inputs used in maize production.

Inputs	Unit	CF coefficients ($\text{kgCO}_{2\text{-eq}} \text{ unit}^{-1}$)	References
Human labour	h	0.700	[46]
Machinery ^a	MJ	0.071	[47]
Diesel fuel	L	2.760	[48]
Nitrogen (N)	kg	4.570	[49]
Phosphate (P_2O_5)	kg	1.180	
Herbicides	kg	23.100	[50]
Electricity (for 2022 Türkiye)	kWh	0.478	[51]
Electricity (for 2023 Türkiye)	kWh	0.469	
Electricity (for 2024 Türkiye) ^b	kWh	0.469	
Irrigation water	m^3	0.077	[37]
Maize Seed	kg	1.930	[52]

^a Machinery use was recorded as working time (h ha^{-1}), converted to machinery energy input using the machinery energy equivalent of 62.70 MJ h^{-1} , and then multiplied by the machinery emission coefficient given in this table.

^b The 2023 national electricity emission factor was used for 2024 because it was the latest available national factor at the time of calculation.

Table 5

AWARE characterization factors for inputs used in maize production.

Inputs	Unit	AWARE ($\text{m}^3_{\text{world-eq}} \text{unit}^{-1}$)	References
Machinery	kg	2.030	[19]
Diesel fuel	MJ	0.009	
Nitrogen (N)	kg	5.520	
Phosphate (P_2O_5)	kg	2.760	
Herbicides	kg	3.600	
Seed	kg	0.441	
Electricity	kWh	0.080	
Water, Türkiye (AWARE _{agri, region})	m^3	7.370	[55]

and footprint calculations, formal statistical hypothesis testing (e.g., ANOVA or mixed-effects modelling) was not performed due to the absence of within-year replication.

Instead, differences between irrigation systems were evaluated using a structured three-year comparative framework. Interannual variability was characterized through year-to-year changes, relative differences (%), and descriptive variability metrics to assess the consistency and robustness of the observed patterns across energy, carbon, and water scarcity indicators. This approach is widely adopted in footprint and life cycle-based assessments relying on aggregated real-world datasets.

3. Results

3.1. Energy calculations

In this study, the effects of sprinkler and center pivot irrigation systems on energy performance were evaluated over three consecutive growing seasons (2022–2024). The results presented in Tables 6 and 7 show the agricultural energy input (AEI), agricultural energy output (AEO), energy use efficiency (EUE), specific energy (SE), energy productivity (EP), and net energy (NE) for silage maize production under both irrigation systems.

Under sprinkler irrigation, EUE slightly decreased from 9.33 in 2022 to 9.03 in 2024, indicating a gradual reduction in energy conversion efficiency over the study period. In contrast, center pivot irrigation maintained consistently higher EUE values of 10.94, 10.57, and 10.81 in 2022, 2023, and 2024, respectively. On average, center pivot irrigation achieved an EUE of 10.77, compared with 9.22 under sprinkler irrigation.

Specific energy followed the opposite trend, with higher values under sprinkler irrigation. SE values under sprinkler irrigation were 1.92, 1.93, and 1.99 MJ kg^{-1} in 2022, 2023, and 2024, respectively, whereas the corresponding values under center pivot irrigation were 1.64, 1.70, and 1.66 MJ kg^{-1} . These results indicate that center pivot irrigation required less energy per unit of dry matter yield produced.

Energy productivity (EP) was also higher under center pivot irrigation. Sprinkler irrigation produced EP values of 0.52, 0.52, and 0.60 kg MJ^{-1} in 2022, 2023, and 2024, respectively, while center pivot irrigation produced higher EP values of 0.61, 0.59, and 0.60 kg MJ^{-1} . This indicates that center pivot irrigation generated more dry matter yield per unit of energy input.

Net energy (NE) gain was positive for both irrigation systems in all years. Under sprinkler irrigation, NE values were 261,776.20, 264,105.38, and 263,190.79 MJ ha^{-1} in 2022, 2023, and 2024, respectively. Under center pivot irrigation, the corresponding values were higher, at 277,146.23, 267,988.11, and 269,757.28 MJ ha^{-1} .

Across the three growing seasons, the relative contribution of agricultural inputs to total AEI differed between irrigation systems (Tables 8 and 9). Under sprinkler irrigation, diesel fuel was the largest contributor to total AEI, although its share slightly decreased from 38.60% in 2022 to 37.05% in 2024. Irrigation water was the second major contributor and increased from 17.03% to 19.80% over the same period, reflecting the higher irrigation water requirement in 2024. Nitrogen fertilizer also represented a substantial share of total AEI, ranging from 17.02% to 17.75%, followed by electricity, which contributed 13.50–14.09%. Machinery accounted for approximately 7.40–7.70%, while the contributions of seed, phosphate fertilizer, herbicides, and human labour remained relatively low.

Under center pivot irrigation, diesel fuel was also the dominant energy input, accounting for 44.67–45.46% of total AEI. Irrigation

Table 6

Energy performance indicators (EUE, SE, EP, and NE) for silage maize production under sprinkler irrigation (2022–2024).

	Unit	Years		
		2022	2023	2024
Dry Matter yield	kg ha^{-1}	16,353.15	16,505.94	16,507.59
AEI	MJ ha^{-1}	31,435.78	31,846.12	32,790.29
AEO	MJ ha^{-1}	293,211.98	295,951.50	295,981.09
EUE	-	9.33	9.29	9.03
SE	MJ kg^{-1}	1.92	1.93	1.99
EP	kg MJ^{-1}	0.52	0.52	0.50
NE	MJ ha^{-1}	261,776.20	264,105.38	263,190.79

Table 7

Energy performance indicators (EUE, SE, EP, and NE) for silage maize production under center pivot irrigation (2022–2024).

	Unit	Years		
		2022	2023	2024
Dry matter yield	kg ha ⁻¹	17,011.50	16,507.59	16,579.20
AEI	MJ ha ⁻¹	27,869.97	27,992.98	27,507.77
AEO	MJ ha ⁻¹	305,016.20	295,981.09	297,265.06
EUE	-	10.94	10.57	10.81
SE	MJ kg ⁻¹	1.64	1.70	1.66
EP	kg MJ ⁻¹	0.61	0.59	0.60
NE	MJ ha ⁻¹	277,146.23	267,988.11	269,757.28

Table 8

Percentage contribution of agricultural inputs to total AEI under sprinkler irrigation (2022–2024).

Inputs	2022 (%)	2023 (%)	2024 (%)
Human labour	0.82	0.81	0.91
Machinery	7.40	7.70	7.59
Diesel fuel	38.60	38.10	37.05
Seed	1.69	1.67	1.62
Phosphate (P ₂ O ₅)	1.93	1.91	1.85
Herbicides	0.68	0.68	0.66
Electricity	14.09	13.90	13.50
Irrigation water	17.03	17.70	19.80
Nitrogen (N)	17.75	17.52	17.02

Table 9

Percentage contribution of agricultural inputs to total AEI under center pivot irrigation (2022–2024).

Inputs	2022 (%)	2023 (%)	2024 (%)
Human labour	0.22	0.22	0.28
Machinery	3.33	3.31	1.55
Diesel fuel	44.87	44.67	45.46
Seed	1.91	1.90	1.93
Phosphate (P ₂ O ₅)	2.18	2.17	2.21
Herbicides	0.77	0.77	0.78
Electricity	5.81	5.79	5.89
Irrigation water	20.88	21.23	21.61
Nitrogen (N)	20.02	19.93	20.29

water was the second largest contributor, with a relatively stable share of 20.88–21.61%, followed by nitrogen fertilizer, which contributed 19.93–20.29%. In contrast, electricity accounted for only 5.79–5.89% of total AEI, which was considerably lower than its share under sprinkler irrigation. Machinery use contributed 3.31–3.33% in 2022 and 2023 but decreased to 1.55% in 2024, while human labour, seed, phosphate fertilizer, and herbicides had minor contributions.

Table 10Carbon footprint (kg CO₂-eq ha⁻¹) of maize production under sprinkler irrigation (2022–2024).

Inputs	Years		
	2022	2023	2024
Human labour	92.61	92.68	106.26
Machinery	165.16	174.06	176.73
Diesel fuel	938.40	938.40	938.40
Nitrogen (N)	566.68	566.68	566.68
Phosphate (P ₂ O ₅)	89.68	89.68	89.68
Herbicides	18.48	18.48	18.48
Electricity (for Türkiye)	587.94	576.87	576.87
Irrigation water	361.90	381.15	438.90
Seed	61.76	61.76	61.76
Total	2882.61	2899.76	2973.76
CF_{kg}(kg CO₂-eq kg⁻¹)	0.18	0.18	0.18

3.2. Carbon footprint (CF)

In this study, the input-related carbon footprint (CF) of silage maize production was assessed over three consecutive growing seasons (2022–2024) under sprinkler and center pivot irrigation systems. The results, expressed on both an area basis and a yield-scaled basis, are presented in [Tables 10 and 11](#).

The carbon footprint was consistently higher under sprinkler irrigation than under center pivot irrigation. Under sprinkler irrigation, total CF values were 2882.61, 2899.76, and 2973.76 kg CO₂-eq ha⁻¹ in 2022, 2023, and 2024, respectively. In contrast, center pivot irrigation resulted in lower CF values of 2400.14, 2404.41, and 2373.99 kg CO₂-eq ha⁻¹ over the same years. On average, the CF was 2918.71 kg CO₂-eq ha⁻¹ under sprinkler irrigation and 2392.85 kg CO₂-eq ha⁻¹ under center pivot irrigation, indicating an approximately 18% lower input-related carbon footprint under center pivot irrigation.

When CF was expressed per unit of dry matter yield, sprinkler irrigation showed stable values of 0.18 kg CO₂-eq kg⁻¹ across all three years. Center pivot irrigation showed lower yield-scaled CF values of 0.14, 0.15, and 0.14 kg CO₂-eq kg⁻¹ in 2022, 2023, and 2024, respectively. These results indicate that center pivot irrigation produced silage maize dry matter with lower input-related greenhouse gas emissions per unit of output.

The percentage contribution of individual inputs to total CFha also differed between irrigation systems ([Tables 12 and 13](#)). Under sprinkler irrigation, diesel fuel was the largest contributor to total CFha, although its share slightly decreased from 32.55% in 2022 to 31.56% in 2024. Electricity was the second major contributor, accounting for 20.40%, 19.89%, and 19.40% of total CFha in 2022, 2023, and 2024, respectively. Nitrogen fertilizer also made a substantial contribution, ranging from 19.06% to 19.66%, while the contribution of irrigation water increased from 12.55% in 2022 to 14.76% in 2024. Machinery, phosphate fertilizer, human labour, seed, and herbicides contributed comparatively smaller shares.

Under center pivot irrigation, diesel fuel was also the dominant contributor to total CFha, accounting for 40.29%, 40.22%, and 40.74% in 2022, 2023, and 2024, respectively. Nitrogen fertilizer was the second largest contributor, with values ranging from 23.57% to 23.87%, followed by irrigation water, which contributed 16.39–16.93%. Electricity accounted for only 8.78–8.96% of total CFha, which was substantially lower than its contribution under sprinkler irrigation.

3.3. Water scarcity footprint (WSF)

The water scarcity footprint (WSF) of silage maize production was assessed over three consecutive years (2022–2024) to evaluate the effects of sprinkler and center pivot irrigation systems on water-related environmental pressure. WSF values were calculated using the AWARE characterization factor for Türkiye and expressed on both an area basis and a yield-scaled basis. The results are summarized in [Tables 14 and 15](#).

For sprinkler irrigation, the total area-based WSF was 35,817.24 m³world-eq ha⁻¹ in 2022, 37,673.43 m³world-eq ha⁻¹ in 2023, and 43,202.19 m³world-eq ha⁻¹ in 2024. For center pivot irrigation, the corresponding values were 38,747.52, 39,543.46, and 39,543.06 m³world-eq ha⁻¹, respectively. These results show that sprinkler irrigation had lower area-based WSF values in 2022 and 2023, whereas center pivot irrigation resulted in a lower WSF value in 2024. The WSF under sprinkler irrigation increased markedly over the study period, mainly due to the higher irrigation water volume in 2024, while the center pivot system showed a more stable WSF pattern across years.

When WSF was expressed per unit of dry matter yield, sprinkler irrigation showed values of 2.19, 2.28, and 2.62 m³world-eq kg⁻¹ in 2022, 2023, and 2024, respectively. The center pivot system showed corresponding values of 2.28, 2.40, and 2.39 m³world-eq kg⁻¹. Thus, sprinkler irrigation had lower yield-scaled WSF values in 2022 and 2023, whereas center pivot irrigation had a lower yield-scaled WSF in 2024. These findings indicate that the WSF advantage was year-dependent rather than consistently associated with one irrigation system.

In both irrigation systems, WSF was overwhelmingly dominated by irrigation water consumption. The contribution of irrigation water to total WSF exceeded 96% in all years, indicating that WSF outcomes were primarily driven by irrigation water volume and the regional AWARE characterization factor rather than by non-water agricultural inputs.

Table 11
Carbon footprint (kg CO₂-eq ha⁻¹) of maize production under center pivot irrigation (2022–2024).

Inputs	Years		
	2022	2023	2024
Human labour	21.98	21.98	27.02
Machinery	65.89	65.89	30.27
Diesel fuel	967.10	967.10	967.10
Nitrogen (N)	566.68	566.68	566.68
Phosphate (P ₂ O ₅)	89.68	89.68	89.68
Herbicides	18.48	18.48	18.48
Electricity (for Türkiye)	215.10	211.05	211.05
Irrigation water	393.47	401.79	401.94
Seed	61.76	61.76	61.76
Total	2400.14	2404.41	2373.99
CF_{kg}(kg CO₂-eq kg⁻¹)	0.14	0.15	0.14

Table 12

Percentage contribution of inputs to CFha under sprinkler irrigation (2022–2024).

Inputs	2022 (%)	2023 (%)	2024 (%)
Human labour	3.21	3.20	3.57
Machinery	5.73	6.00	5.94
Diesel fuel	32.55	32.36	31.56
Seed	2.14	2.13	2.08
Phosphate (P2O5)	3.11	3.09	3.02
Herbicides	0.64	0.64	0.62
Electricity	20.40	19.89	19.40
Irrigation water	12.55	13.14	14.76
Nitrogen (N)	19.66	19.54	19.06

Table 13

Percentage contribution of inputs to CFha under center pivot irrigation (2022–2024).

Inputs	2022 (%)	2023 (%)	2024 (%)
Human labour	0.92	0.91	1.14
Machinery	2.75	2.74	1.28
Diesel fuel	40.29	40.22	40.74
Seed	2.57	2.57	2.60
Phosphate (P2O5)	3.74	3.73	3.78
Herbicides	0.77	0.77	0.78
Electricity	8.96	8.78	8.89
Irrigation water	16.39	16.71	16.93
Nitrogen (N)	23.61	23.57	23.87

Table 14WSF ($\text{m}^3_{\text{world-eq}} \text{ha}^{-1}$) of maize production under sprinkler irrigation (2022–2024).

Inputs	Years		
	2022	2023	2024
Machinery	70.27	74.06	75.19
Diesel fuel	108.24	108.24	108.37
Nitrogen (N)	684.48	684.48	684.48
Phosphate (P ₂ O ₅)	209.76	209.76	209.76
Herbicides	2.88	2.88	2.88
Electricity	98.40	98.40	98.40
Seed	14.11	14.11	14.11
Water, Türkiye (AWAREagri, region)	34,639.00	36,481.50	42,009.00
Total	35,817.24	37,673.43	43,202.19
WSF($\text{m}^3_{\text{world-eq}} \text{kg}^{-1}$)	2.19	2.28	2.62

Table 15WSF ($\text{m}^3_{\text{world-eq}} \text{ha}^{-1}$) of maize production under center pivot irrigation (2022–2024).

Inputs	Years		
	2022	2023	2024
Machinery	28.03	28.01	12.88
Diesel fuel	111.55	111.55	111.55
Nitrogen (N)	684.48	684.48	684.48
Phosphate (P ₂ O ₅)	209.76	209.76	209.76
Herbicides	2.88	2.88	2.88
Electricity	36.00	36.00	36.00
Seed	14.11	14.11	14.11
Water, Türkiye (AWAREagri, region)	37,660.70	38,456.66	38,471.40
Total	38,747.52	39,543.46	39,543.06
WSF($\text{m}^3_{\text{world-eq}} \text{kg}^{-1}$)	2.28	2.40	2.39

Table 16

Comparative performance of sprinkler and center pivot irrigation systems (2022–2024) based on energy, carbon, and water scarcity indicators.

Indicator	Sprinkler (2022)	Sprinkler (2023)	Sprinkler (2024)	Center pivot (2022)	Center pivot (2023)	Center pivot (2024)	Sprinkler (Mean)	Center pivot (Mean)	Relative change of center pivot vs. sprinkler (%)
Dry matter Yield	16,353.15	16,505.94	16,507.59	17,011.50	16,507.59	16,579.20	16,455.56	16,699.43	1.48
EUE	9.33	9.29	9.03	10.94	10.57	10.81	9.22	10.77	16.89
SE	1.92	1.93	1.99	1.64	1.70	1.66	1.95	1.66	−14.38
EP	0.52	0.52	0.50	0.61	0.59	0.60	0.51	0.60	16.88
NE	261,776.20	264,105.38	263,190.79	277,146.23	267,988.11	269,757.28	263,024.13	271,630.54	3.27
CF	0.18	0.18	0.18	0.14	0.15	0.14	0.18	0.14	−22.22
WSF	2.19	2.28	2.62	2.28	2.40	2.39	2.36	2.36	0.00

Note: Relative change was calculated as: $[(\text{Center pivot mean} - \text{Sprinkler mean}) / \text{Sprinkler mean}] \times 100$ using the rounded mean values presented in the table. Positive values indicate higher values under center pivot irrigation, whereas negative values indicate lower values. For SE, CF, and WSF, lower values indicate better resource-use or environmental performance. CF is expressed as kg CO₂-eq kg^{−1} dry matter, and WSF is expressed as m³ world-eq kg^{−1} dry matter.

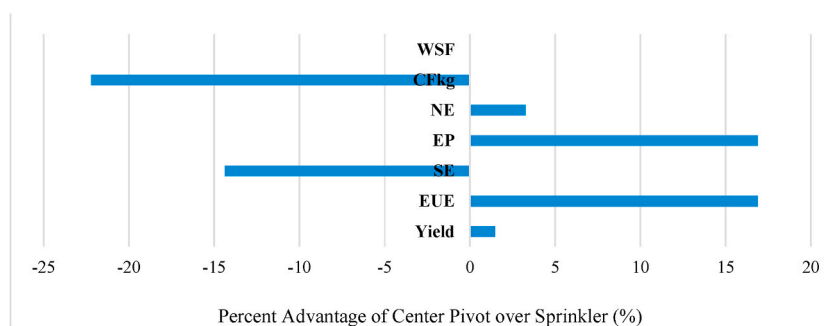


Fig. 4. Percentage differences between center pivot and sprinkler irrigation systems calculated from mean indicator values for the period 2022–2024.

3.4. Overall comparative performance

Overall, the three-year comparative assessment of sprinkler and center pivot irrigation systems is presented in Table 16 and Fig. 4. Based on the mean values presented in Table 16, dry matter yield increased by 1.48% under center pivot irrigation compared with sprinkler irrigation. Energy use efficiency increased by 16.89%, while specific energy decreased by 14.38%, indicating a lower energy requirement per unit of dry matter yield. Energy productivity also increased by 16.88%, and net energy was 3.27% higher under center pivot irrigation. The input-related carbon footprint per unit of dry matter yield decreased by 22.22% under center pivot irrigation. In contrast, the mean water scarcity footprint was identical between the two systems, with no relative change. However, WSF showed a year-dependent pattern, with sprinkler irrigation having lower values in 2022 and 2023, whereas center pivot irrigation showed a lower value in 2024.

4. Discussion

This study evaluated how irrigation technology shapes the energy performance, input-related carbon footprint, and water scarcity footprint of silage maize production under semi-arid commercial farm conditions. The results indicate that irrigation technology influenced energy and carbon performance more clearly than water scarcity footprint. Center pivot irrigation showed better energy performance and lower input-related carbon footprint than sprinkler irrigation, whereas WSF did not consistently favor one system across all years. This pattern highlights the central scientific finding of the study: irrigation technology affects sustainability performance not only through the amount of water applied, but also through the structure of energy use, field operations, and input-related emissions. Therefore, energy, carbon, and water scarcity indicators should be interpreted together rather than independently when evaluating irrigation systems.

4.1. Evaluation in terms of energy calculations

The higher EUE observed under center pivot irrigation indicates that this system converted energy inputs into silage maize dry matter more efficiently than sprinkler irrigation under the evaluated field conditions. This advantage was also supported by lower SE and higher EP values, showing that center pivot irrigation required less energy per unit of dry matter yield and produced more output per unit of energy input. Lower SE values are generally associated with reduced energy intensity per unit of production, while higher EP values indicate greater output per unit of energy consumed; therefore, these indicators are widely used to interpret both energy efficiency and production sustainability in agricultural systems [43,56–58]. Thus, the energy-related advantage of center pivot irrigation was not simply a result of yield differences, but was mainly associated with the lower total energy requirement and a more favorable energy input structure.

The analysis of energy input contributions further explains this pattern. Under sprinkler irrigation, diesel fuel was the largest contributor to total AEI, followed by irrigation water, nitrogen fertilizer, and electricity. Under center pivot irrigation, diesel fuel also represented the dominant energy input, while irrigation water and nitrogen fertilizer were the next major contributors. However, the shares of electricity and machinery were lower under center pivot irrigation than under sprinkler irrigation. This difference is important because irrigation systems influence not only water application but also pumping requirements, operational time, machinery use, and electricity demand. Therefore, the improved energy performance of center pivot irrigation can be linked to its lower energy intensity per unit of silage maize dry matter rather than to water use alone.

These findings are consistent with previous studies emphasizing that irrigation technology and input structure strongly affect energy efficiency in crop production systems. Similar conclusions were reported by Ref. [59], who demonstrated that climate-smart irrigation practices significantly improved energy use efficiency while reducing environmental impacts in maize production systems. This suggests that the energy intensity of agricultural inputs should be analyzed together with irrigation technology when evaluating production sustainability. Likewise [60], found that nitrogen fertilizer and electricity were the two largest contributors to energy consumption in barley production across different irrigation methods. Using Data Envelopment Analysis [61], also showed that

different irrigation methods significantly affect total energy consumption and energy-saving potential. Recent studies have further emphasized that improving irrigation efficiency can enhance energy performance while supporting sustainable resource management [62].

However, irrigation efficiency and energy savings do not always change in the same direction. In some cases, water-saving irrigation practices may increase energy requirements due to higher pumping pressure, deeper groundwater abstraction, or greater hydraulic demand. This trade-off was also noted by Ref. [63], who reported that despite water savings, increased pumping requirements associated with declining groundwater levels led to higher energy consumption. Therefore, irrigation management should not focus solely on reducing water use, but should also optimize energy use per unit of crop output. In this context, EUE, SE, EP, and NE provide complementary indicators for understanding whether an irrigation system improves overall resource-use performance.

4.2. Assessment in terms of carbon footprint

The input-related carbon footprint results showed that center pivot irrigation had a lower carbon footprint per unit of dry matter yield than sprinkler irrigation. This reduction was mainly associated with lower electricity- and machinery-related emission contributions under center pivot irrigation. Although diesel fuel represented the largest share of total CFha in both systems, its higher proportional contribution under center pivot irrigation should be interpreted carefully. The higher share of diesel fuel does not necessarily indicate a higher total carbon footprint; rather, it reflects the lower contribution of other emission sources, particularly electricity and machinery, in the center pivot system.

Under sprinkler irrigation, diesel fuel was the dominant source of input-related emissions, followed by electricity, nitrogen fertilizer, and irrigation water. Under center pivot irrigation, diesel fuel remained the largest contributor, followed by nitrogen fertilizer and irrigation water, while electricity accounted for a much smaller share than under sprinkler irrigation. This indicates that the carbon performance of irrigation systems depends strongly on the energy profile of the production system. In particular, differences in electricity consumption, machinery use, and water delivery requirements can substantially modify the carbon footprint even when fertilizer and seed inputs are kept constant between systems.

These findings demonstrate that the carbon footprint of irrigated silage maize production is sensitive not only to irrigation technology but also to the structure of farm energy use. This relationship is increasingly discussed within the water–energy nexus, where irrigation decisions directly affect water use, pumping energy demand, and input-related greenhouse gas emissions [64]. Similar trends have been reported in previous studies, where mechanization, fertilization, and energy use were identified as major contributors to agricultural GHG emissions [19,65]. Although irrigation can increase total energy demand, improvements in system efficiency may reduce emissions per unit of production when lower energy input is required to obtain a comparable output. This aligns with evidence indicating that optimized irrigation practices can contribute to lowering agricultural greenhouse gas emissions [66].

The results also support previous findings that efficient input management is critical for reducing greenhouse gas emissions in crop production systems. Studies on sorghum × sudangrass hybrid [43], cotton [67], wheat–maize [68], maize [19], and rice–wheat systems [69] have similarly emphasized the importance of managing fertilizers, energy inputs, and field operations to reduce agricultural carbon footprints. Therefore, improving energy efficiency, reducing electricity and machinery-related emissions, and integrating lower-carbon energy sources into irrigation systems represent important pathways for reducing the input-related carbon footprint of irrigated agriculture. Therefore, the carbon footprint results should be interpreted within the defined input-related system boundary, and further assessment of direct soil-derived N₂O emissions would provide a more complete understanding of irrigation-related greenhouse gas dynamics.

4.3. Assessment in terms of water scarcity footprint

Unlike the energy and carbon indicators, the water scarcity footprint did not show a consistent advantage for center pivot irrigation across all years. Sprinkler irrigation had lower WSF values in 2022 and 2023, whereas center pivot irrigation showed a lower WSF value in 2024. On a three-year mean basis, the yield-scaled WSF values were identical between the two systems when expressed with two decimal places. This result is important because it indicates that WSF was not primarily controlled by irrigation technology alone. Instead, WSF was mainly governed by the total irrigation water volume and the regional AWARE characterization factor.

The higher WSF observed under sprinkler irrigation in 2024 was mainly driven by the higher irrigation water volume recorded for that year. Given the dominant contribution of irrigation water to total WSF, this higher irrigation volume directly increased the water scarcity footprint of the sprinkler system. However, the available farm records did not allow a detailed separation of the specific management-related causes of this increase. The higher water use may have been associated with farm-level irrigation scheduling, longer irrigation duration, operational decisions, or lower application efficiency under sprinkler irrigation. Therefore, the 2024 WSF result should be interpreted as a year-specific outcome of irrigation volume and farm-level water management rather than as a fixed characteristic of the sprinkler system itself.

In both irrigation systems, irrigation water consumption accounted for more than 96% of the total WSF. This dominance shows that the water scarcity footprint is fundamentally driven by water use rather than by non-water agricultural inputs. Therefore, even if an irrigation technology improves energy performance or reduces input-related carbon emissions, it will not necessarily reduce WSF unless it also reduces total irrigation water consumption under the same regional scarcity conditions. This explains why center pivot irrigation showed clear advantages in energy and carbon performance but did not show a consistent WSF advantage across all years.

The WSF values obtained in this study were higher than those reported in some previous studies. For example [19], reported a WSF value of 5613 m³ world-eq ha⁻¹ for maize production, while [70] identified a range between 1990 and 8280 m³ world-eq ha⁻¹. This

difference can largely be attributed to the relatively high AWARE characterization factor associated with water-limited regions such as Türkiye. The AWARE indicator reflects the environmental relevance of water consumption under regional scarcity conditions, where each unit of water consumed may impose a higher environmental burden [71]. Therefore, WSF results should be interpreted in relation to both the amount of irrigation water applied and the regional characterization factor used in the assessment.

These findings highlight that reducing water scarcity impacts in irrigated agriculture requires more than a shift in irrigation technology. While center pivot irrigation improved energy and carbon performance under the evaluated conditions, WSF reduction depends primarily on controlling absolute irrigation water consumption and adapting irrigation scheduling to local water availability. Therefore, irrigation planning should integrate water volume, energy demand, carbon emissions, and regional scarcity conditions within a single decision framework. This integrated interpretation provides a clearer link between the study objective, the selected indicators, and the main results: center pivot irrigation may be more energy- and carbon-efficient under similar commercial farm conditions, but water scarcity performance remains strongly year-dependent and region-specific.

5. Limitations

This study has some limitations that should be considered when interpreting the findings. The analysis was based on measured data from a single commercial farm and did not include replicated randomized field trials. Therefore, no statistical significance testing was performed, and the results should be interpreted as a field-based case-study comparison rather than as evidence from a fully controlled experimental design. The use of identical fertilizer, seed, and herbicide application rates under both irrigation systems should also be interpreted as a design feature of this case-study comparison, aimed at reducing management-related variability between the two irrigation areas. In addition, the analysis focused on energy use efficiency, carbon footprint, and water scarcity footprint, while economic costs, equipment investment, maintenance requirements, and long-term effects on soil properties and groundwater resources were not included.

Direct soil-derived N_2O emissions from nitrogen fertilizer application were not included in the carbon footprint calculation. This may have resulted in an underestimation of the absolute carbon footprint values, since N_2O emissions can represent an important component of agricultural greenhouse gas emissions. However, the same nitrogen application rate was used under both irrigation systems, and the present assessment focused on input-related carbon footprint rather than a full field-scale greenhouse gas balance. Soil N_2O emissions are strongly affected by soil moisture, aeration, temperature, nitrogen availability, and irrigation regime. Therefore, sprinkler and center pivot irrigation may influence N_2O emissions differently by altering soil moisture distribution, wetting–drying cycles, oxygen availability, and nitrogen transformation processes. Nevertheless, because direct N_2O fluxes and continuous soil moisture dynamics were not measured, the potential differential effect of irrigation technology on soil-derived N_2O emissions could not be evaluated in this study. Future studies should combine direct N_2O flux measurements, soil moisture monitoring, nitrogen dynamics, and IPCC-based emission estimates to provide a more complete greenhouse gas assessment of irrigation systems.

The applicability of the findings should also be interpreted within the regional and management conditions of the study. This research was conducted on a large commercial farm in Ankara Province, Central Anatolia, Türkiye, where irrigated silage maize production is carried out under semi-arid climatic conditions. Both irrigation systems were supplied from the same water source and pumping station; therefore, the main pumping infrastructure and water-lifting conditions were common to both systems. However, detailed data on water conveyance distance, system-level pressure requirements, friction losses, pumping station efficiency, and disaggregated diesel consumption were not available. Therefore, the observed differences in energy performance should be interpreted as the combined result of irrigation system characteristics, field scale, and site-specific operational conditions rather than as a purely technological effect. Accordingly, the findings should not be directly generalized to all irrigated agricultural systems without considering local water, energy, climate, hydraulic, and management conditions.

6. Conclusions

This study evaluated the energy performance, input-related carbon footprint, and water scarcity footprint of silage maize production under sprinkler and center pivot irrigation systems using three-year field-based data from a large commercial farm in Ankara Province, Central Anatolia, Türkiye. The results indicated that center pivot irrigation was associated with more favorable energy performance than sprinkler irrigation under the evaluated case-comparison conditions. This was reflected in higher energy use efficiency and energy productivity, together with lower specific energy, indicating lower energy use per unit of dry matter yield within the observed production system.

Center pivot irrigation was also associated with a lower input-related carbon footprint per unit of dry matter yield than sprinkler irrigation. This difference was mainly related to lower electricity- and machinery-related emission contributions under center pivot irrigation. However, because the center pivot fields were considerably larger than the sprinkler-irrigated fields, the observed differences in energy and carbon performance should not be attributed solely to irrigation technology. Scale-related effects and field-specific operational conditions may also have contributed to the observed differences.

The water scarcity footprint did not show a consistent advantage for one irrigation system across all years. The mean WSF values were similar between the two systems, and the yearly pattern varied: sprinkler irrigation showed lower WSF values in 2022 and 2023, whereas center pivot irrigation showed a lower value in 2024. Therefore, WSF should be interpreted as a year-dependent indicator mainly governed by irrigation water volume and the regional AWARE characterization factor rather than by irrigation technology alone.

Overall, the findings suggest that center pivot irrigation may support more energy- and carbon-efficient silage maize production

under the specific semi-arid commercial farm conditions evaluated in this study. Nevertheless, these results should be interpreted with caution because the comparison was based on real-world fields differing in scale and site-specific operational characteristics. Therefore, the findings should not be generalized as a direct technological effect across all production contexts or environmental indicators. Irrigation planning should consider energy, carbon, and water scarcity indicators together, while field size, hydraulic conditions, irrigation volume, water availability, and local water scarcity factors should be carefully evaluated before broader implementation.

Funding

This study has been supported by the Recep Tayyip Erdoğan University Development Foundation (Grant number: 02026005013338).

CRediT authorship contribution statement

Ömer Eren: Conceptualization, Investigation, Methodology, Writing – original draft. **Halit Tutar:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Muhammed İkbāl Çatal:** Conceptualization, Writing – original draft, Writing – review & editing. **Handan Paytsun:** Conceptualization, Data curation, Investigation.

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.

Acknowledgements

This article was presented as an oral abstract in Turkish at the 35th National Agricultural Mechanization and Energy Congress (TARMEK 2024) (5 September 2024-Kırşehir).

Data availability

Data will be made available on request.

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