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Energy Use Efficiency and Greenhouse Gas Emissions in Industrial Hemp (*Cannabis sativa* L.) Production Under Semi-Arid Central Anatolian Conditions

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Abstract

The objective of this study was to determine the energy balance and greenhouse gas (GHG) emissions associated with the production of industrial hemp (*Cannabis sativa* L.) under semi-arid Central Anatolian conditions. A field experiment was conducted using the registered industrial hemp cultivar 'Vezir' under semi-arid conditions, and energy use indicators and greenhouse gas emissions were quantified through an input–output analysis based on field-level agricultural inputs and biomass yield. The total energy input was calculated as 13,688.50 MJ ha^{-1}, of which chemical fertilizers (54.339%) and diesel fuel (32.09%) jointly accounted for more than 90%, followed by irrigation water (4.66%), machinery 2.87%), and human labor (0.21%). The corresponding energy output reached 388,073.80 MJ ha^{-1}, yielding an energy use efficiency of 28.35, a specific energy of 0.62 MJ kg^{-1}, an energy productivity of 1.61 kg MJ^{-1} and a net energy of 374,385.28 MJ ha^{-1}. Of the total energy input, 36.95% was direct and 63.05% indirect, while 89.35% originated from non-renewable sources and only 10.65% originated from renewable sources. Total GHG emissions amounted to 590.14 kg CO_2 eq ha^{-1}, with diesel fuel and nitrogen fertilizer identified as the dominant emission sources. These findings indicate that industrial hemp combines high productivity with low environmental burdens under semi-arid conditions. Beyond its favorable energy balance, hemp offers potential contributions to climate-smart agriculture through efficient resource use, reduced greenhouse gas emissions per unit of output, and diversification of cropping systems in water-limited environments. Therefore, industrial hemp can support the transition toward more sustainable and resilient agricultural systems in semi-arid regions of Türkiye and similar agroecological zones.

Keywords: energy productivity; greenhouse gas emissions; net energy; industrial hemp; Central Anatolia; Türkiye

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1. Introduction

Hemp (*Cannabis sativa* L.) is an annual herbaceous plant species belonging to the Cannabaceae family, cultivated for thousands of years and considered one of the oldest fiber, seed, and oil crops in human history. The species is dioecious, with separate male and female plants, and is characterized by a deep tap-root system, an erect stem reaching 1.5–5 m in height, palmately compound leaves, and small wind-pollinated flowers [1,2]. Owing to its remarkable phenotypic plasticity, hemp can be grown for a wide range of end-uses, including bast fiber for textiles and composites, hurds (shiv) for construction materials and animal bedding, seeds and seed oil for food and feed, and inflorescences for cannabidiol (CBD) and other non-psychoactive cannabinoids [3,4]. Industrial hemp cultivars are legally distinguished from drug-type cannabis by a tetrahydrocannabinol (THC) content below the regulatory threshold of 0.2–0.3%, depending on the country [2,5].

Globally, hemp cultivation has experienced a marked revival during the last two decades, driven by growing demand for sustainable bio-based materials, the legalization of industrial hemp in many countries, and the increasing scientific interest in cannabinoids. According to FAO [6], world hemp fiber and tow production is approximately 200,000 tons, with China, France, Canada, the Russian Federation, and several European Union countries being the leading producers. Hemp is also valued for its agronomic and environmental advantages: rapid canopy closure that suppresses weeds, low requirements for synthetic pesticides, deep rooting that improves soil structure, high biomass productivity per unit area, and a substantial capacity for atmospheric CO_2 sequestration [7,8]. These traits make hemp a strong candidate for inclusion in sustainable cropping systems and for diversifying rotations dominated by cereals.

Türkiye lies within one of the historical centers of hemp cultivation, and the species has been grown traditionally in the Black Sea region, particularly in Kastamonu (Taşköprü), Samsun and surrounding provinces, mainly for fiber and seed production [9,10]. After a long period of decline driven by the prohibition of cannabis-related products and competition from synthetic fibers, hemp cultivation has been re-evaluated in recent years within the framework of the "Regulation on Hemp Cultivation and Control" published by the Republic of Türkiye's Ministry of Agriculture and Forestry in 2016 [11] and subsequently revised on 31 January 2026 [12]. Under this regulation, the cultivation of industrial hemp for fiber, seed, stalk and similar purposes is currently permitted in 21 designated provinces of Türkiye—namely Amasya, Antalya, Bartın, Burdur, Çorum, İzmir, Karabük, Kastamonu, Kayseri, Konya, Kütahya, Malatya, Ordu, Rize, Samsun, Sinop, Sivas, Tokat, Uşak, Yozgat and Zonguldak—and in all districts of these provinces. Hemp cultivation in Konya province was approved as of the 2024 production year, considering the suitability of the province for hemp adaptation, the increasing need for industrial raw materials, and the value of hemp as an alternative crop in rotation systems dominated by cereals, sugar beets and maize. In parallel, the first domestic industrial hemp cultivars were registered in 2021 by the Black Sea Agricultural Research Institute and Ondokuz Mayıs University, providing certified, low-THC seed material for producers in newly authorized provinces such as Konya [12].

Beyond its agronomic and environmental advantages, industrial hemp is distinguished by the wide range of value-added products that can be obtained from different plant organs, contributing to its growing importance within sustainable bio-based value chains. Hemp seed is rich in highly digestible protein (20–25%), essential fatty acids—particularly linoleic (omega-6) and α-linolenic (omega-3) acids in a nutritionally favorable ratio close to 3:1-dietary fiber, tocopherols, and essential minerals such as magnesium, phosphorus, and iron [13–16]. Hemp oil, obtained by cold pressing the seeds, is increasingly used in functional foods, cosmetics and nutraceuticals [3]. The bast fiber of hemp is one of the strongest natural fibers known and is used in textiles, paper, biocomposites, automotive interior parts and insulation materials, while the woody core (Hurd) is processed into hempcrete, particle boards and absorbent animal bedding [4,8,17,18]. Furthermore, non-psychoactive cannabinoids—mainly CBD—and a wide range of phenolic and terpenoid compounds extracted from inflorescences exhibit antioxidant, anti-inflammatory and neuroprotective properties, supporting their use in pharmaceutical and personal-care products [3,18,19].

The transition towards sustainable agricultural systems is a central component of global efforts to improve resource efficiency, mitigate climate change and achieve the Sustainable Development Goals (SDGs) [20]. SDG 2 (Zero Hunger), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) highlight the need for agricultural production systems capable of generating high output while minimizing environmental impacts and resource consumption [20]. Within this context, industrial hemp has attracted increasing attention as a strategic crop for the emerging bioeconomy due to its versatility and broad range of applications [21]. Besides supplying raw materials for food, fiber, construction materials, and bioenergy, hemp can contribute to reducing dependence on fossil-based resources and promoting more sustainable and circular agricultural value chains [17,22].

In recent years, research addressing the sustainability and reduction in environmental impacts of agricultural production has gained substantial importance. Agricultural activities, owing to their energy consumption and the use of inputs such as synthetic fertilizers and pesticides, are well-known sources of greenhouse gas (GHG) emissions [23]. N_2O emissions associated with nitrogen fertilization, electricity used for irrigation, and fuel consumed during soil tillage operations are key determinants of the environmental performance of cropping systems [23,24]. In hemp production, energy inputs and fuel-related emissions arising from soil preparation, sowing, irrigation, fertilization, plant protection, harvesting, and post-harvest operations must be quantified to objectively assess its environmental footprint and to compare hemp with conventional field crops grown in the same region.

Numerous studies have evaluated energy balance and GHG emissions in agricultural products, including strawberries [25], oranges [26], berries [27], Kaman walnuts [28], kumquats [29], wheat [30], sesame [31], lavender [32], cotton [33], quinoa [34], kiwis [35], avocados [36], lemons [37], pecan walnuts [38], white cherries [39], common vetches [40], cumin [41], potatoes [42], and blackberries [43]. However, comprehensive studies focusing specifically on energy balance and GHG emissions in industrial hemp production under semi-arid Central Anatolian conditions are limited.

The significance of the present study lies in its holistic assessment of energy use and GHG emissions associated with the production of industrial hemp grown in Çumra district of Konya province, located in the semi-arid Central Anatolian Region of Türkiye. Following the inclusion of Konya in the list of provinces officially authorized for industrial hemp cultivation by the Ministry of Agriculture and Forestry, hemp is emerging as a promising alternative crop for the Çumra plain, where water resources are increasingly scarce, and the cropping pattern is dominated by irrigated cereals, sugar beets, and maize. The findings are expected to contribute to evaluating the environmental sustainability of hemp production, to estimating its carbon footprint, and to developing strategies for reducing energy use and GHG emissions in this newly introduced crop. In this context, analyzing the energy inputs and GHG emissions in hemp production through an input–output approach enables an objective and comparable evaluation of the environmental performance of hemp under Çumra conditions.

2. Materials and Methods

The study was carried out during the 2024–2025 growing season in Çumra district of Konya province in Türkiye's Central Anatolia Region. Çumra is situated approximately 43 km southeast of Konya city center, with geographical coordinates of approximately 37°34′23″ N and 32°46′28″ E, at an elevation of approximately 1015 m above sea level, on the eastern part of the Konya Closed Basin. The district lies within the continental, semi-arid climate zone of Central Anatolia, characterized by hot and dry summers and cold winters, a long-term mean annual precipitation of approximately 300–325 mm and a mean annual temperature of around 11–12 °C. The dominant soils of the Çumra plain are alluvial and vertosol soils with a clayey texture, alkaline reaction and generally high lime content, and the district is among the most extensive and productive irrigated agricultural areas of the country, supplied mainly from the Apa Dam, the Blue Tunnel (Mavi Tünel) Project and groundwater resources [44–46].

The total production area was 2.5 hectares (25,000 m^2), and the experiment was conducted on a 0.10 hectare plot using a randomized complete block design with three replications. The randomized complete block design with three replications was established to ensure reliable field observations and biomass production under local growing conditions. However, the objective of the present study was not to compare different agronomic treatments, cultivars, or management practices, but to quantify the energy use efficiency and greenhouse gas (GHG) emissions of the existing industrial hemp production system. Therefore, energy input–output calculations and GHG emission assessments were performed using the total amounts of agricultural inputs applied per hectare and the corresponding biomass yield at the production-system level. Since the study did not include independent treatment groups for comparison, statistical analyses such as analysis of variance, standard deviations, confidence intervals, or significance tests were not applicable to the calculated energy and GHG indicators. The registered Turkish industrial hemp cultivar 'Vezir' (*Cannabis sativa* L.), developed by the Black Sea Agricultural Research Institute and Ondokuz Mayıs University and officially registered in 2021, was used as plant material. 'Vezir' is a monoecious, low-THC (<0.2%) cultivar bred specifically for Turkish ecological conditions and suitable for dual-purpose (fiber and seed) production resources [47]. The cultivation was carried out under the official hemp cultivation permit issued by the Konya Provincial Directorate of Agriculture and Forestry, in accordance with the provisions of the "Regulation on Hemp Cultivation and Control" resources [12]. Sowing was carried out in the second half of April with a precision seed-drill at a row spacing of 28 cm and an intra-row spacing of 3–4 cm, with a seeding rate of 25 kg ha^{-1}, following conventional soil preparation consisting of one moldboard plowing, one cultivator tilling and one float-leveling operation. Fertilization was applied based on soil-test recommendations and on the agronomic guidelines reported for industrial hemp under semi-arid conditions. Plant protection consisted of the application of selective herbicides at the early growth stage, while no fungicide or insecticide treatments were required during the growing season. Irrigation was applied through a sprinkler system using groundwater. Harvest of the biomass was carried out at full physiological maturity in the second half of September, and the air-dried biomass was weighed in the field.

Energy inputs in industrial hemp production, including human labor, machinery, chemical fertilizers, diesel fuel, and irrigation water (Table 1), were determined per hectare. The energy equivalent of seeds and biomass was measured according to the ASTM D5468-95 standard using an IKA C200 model calorimeter (IKA, Staufen im Breisgau, Germany) with a maximum measurement range of 40,000 J, a measurement accuracy of ±0.1 J, and four different operating modes [48].

Table 1. Energy equivalents used in industrial hemp production.

Inputs	Unit	Energy Equivalent (MJ unit^{-1})	References
Human labor	h	1.96	[49,50]
Tractor	h	25.40	[51,52]
Plow	h	18.70	[51,52]
Cultivator	h	14.00	[51,52]
Sowing machinery	h	22.00	[51,52]
Combine harvester	h	87.63	[51,52]
Trailer	h	64.10	[51,52]
Chemical fertilizers			
Nitrogen (N)	kg	60.60	[50,51]
Phosphorus (P)	kg	11.10	[53,54]
Diesel fuel	L	56.31	[53,54]
Irrigation water	m^3	1.02	[54,55]
Seed	kg	31.70	Measured
Output			
Industrial hemp biomass	kg	19.28	Measured

The energy output of hemp biomass was calculated using the corresponding energy equivalents reported in the literature. The formulas applied were used to calculate energy use efficiency, specific energy, energy productivity, and net energy in hemp production [55–58]:

$$\text{Energy use efficiency} = \text{Energy output (MJ ha}^{-1}\text{)/Energy input (MJ ha}^{-1}\text{)} \quad (1)$$

$$\textit{Specific energy} = \textit{Energy input}\ \text{(MJ ha}^{-1}\text{)}/\textit{Hemp output}\ \text{(kg ha}^{-1}\text{)} \quad (2)$$

$$\textit{Energy productivity} = \textit{Hemp output}\ \text{(kg ha}^{-1}\text{)}/\textit{Energy input}\ \text{(MJ ha}^{-1}\text{)} \quad (3)$$

$$\textit{Net energy} = \textit{Energy output}\ \text{(MJ ha}^{-1}\text{)} - \textit{Energy input}\ \text{(MJ ha}^{-1}\text{)} \quad (4)$$

GHG emissions for hemp production (Table 2) were calculated by multiplying the GHG equivalent emission values of inputs by the corresponding amounts used per hectare. The emission ratio was determined using the formula adapted from Hughes et al. [59] by Karaağaç et al. [60].

Table 2. GHG emission equivalents are used in industrial hemp production.

Inputs	Unit	GHG Equivalent (kg CO_2 eq unit^{-1})	References
Tractor and machinery	MJ	0.071	[54,61]
Nitrogen (N)	kg	1.300	[23,50]
Phosphorus (P)	kg	0.200	[23,50]
Diesel fuel	L	2.760	[50,61]
Seed	kg	7.630	[62,63]

The GHG emissions (kg CO_2 eq ha^{-1}) related to the inputs used to grow 1 ha of hemp were calculated as follows, where R (i) is the application ratio of input i (unit$_{input}$ ha^{-1}) and EF (i) is the GHG emission coefficient of input i (kg CO_2 eq unit$_{input}$$^{-1}$). An index was determined to express the amount of emitted kg CO_2 eq per kg of yield as in the following formula:

$$GHGha = \sum_{i=1}^{n} R(i) \times EF(i) \quad (5)$$

The GHG ratio is an index expressing the amount of GHG emissions per unit yield. In the calculation of the GHG ratio, the formula adapted from Houshyar et al. [64] and Khoshnevisan et al. [65] by Karaağaç et al. [60] was used, where I_{GHG} is the GHG ratio (kg CO_2 eq kg^{-1}), and Y is the yield expressed in kg per hectare:

$$I_{GHG} = GHGha/Y \quad (6)$$

The input energy was separated into direct, indirect, renewable and non-renewable forms [52,56,64]. Energy balance calculations, energy input types, GHG emissions, and the share of inputs related to hemp production were calculated.

The system boundary included emissions associated with machinery use, diesel fuel consumption, and the production of nitrogen and phosphorus fertilizers. Direct and indirect soil N_2O emissions resulting from nitrogen fertilizer application were not included. Therefore, the calculated value represents input-related GHG emissions within the defined field-level boundary rather than the complete carbon footprint of industrial hemp production.

3. Results and Discussion

The energy balance associated with the production of industrial hemp is detailed in Table 3. The energy inputs in hemp production were calculated, respectively, as chemical fertilizers, 7444.80 MJ ha^{-1} (54.39%); diesel fuel, 4392.18 MJ ha^{-1} (32.09%); irrigation water, 637.50 MJ ha^{-1} (4.66%); machinery, 393.11 MJ ha^{-1} (2.87%); and human labor, 28.42 MJ ha^{-1} (0.21%). Total energy input of industrial hemp production was calculated as 13,688.50 MJ ha^{-1}, and energy output as 388,073.80 MJ ha^{-1}.

Table 3. Energy balance of industrial hemp production.

Inputs	Unit	Energy Equivalent (MJ $unit^{-1}$)	Input Used per Ha (unit ha^{-1})	Energy Value (MJ ha^{-1})	Ratio (%)
Human labor	h	1.96	14.50	28.42	0.21
Tractor	h	25.40	6.17	156.63	1.14
Plow	h	18.70	2.50	46.75	0.34
Cultivator	h	14.00	1.67	23.33	0.17
Sowing machinery	h	22.00	0.67	14.67	0.11
Combine harvester	h	87.63	1.00	87.63	0.64
Trailer	h	64.10	1.00	64.10	0.47
Seed	kg	31.70	25	792.50	5.79
Chemical fertilizers					
Nitrogen (N)	kg	60.60	106.00	6423.60	46.93
Phosphorus (P)	kg	11.10	92.00	1021.20	7.46
Diesel fuel	L	56.31	78.00	4392.18	32.09
Irrigation water	m^3	1.02	625.00	637.50	4.66
Total				**13,688.50**	**100.00**
Output					
Industrial hemp biomass (86% dry matter)	kg	19.28	329,460.50	15.10	
Hemp seed yield	kg	31.70	58,613.30	84.90	
Total			**388,073.80**	**100.00**	

The dominant role of chemical fertilizers in the total energy input (54.39%) agrees with the findings reported for several field and orchard crops grown under Türkiye conditions Koçtürk and Engindeniz [66]. Çıtıl et al. [28] calculated the share of chemical fertilizers as 39.87% for Kaman walnut, Demir and Gökdoğan [67] reported a higher share of 55.70% for peach, while comparatively lower shares were recorded for white cherry (23.24%) by

Çelik et al. [39] and kumquat (30.58%) by Özbek and Gökdoğan [29]. For field crops, Özbek et al. [31] reported a share of 54.99% for sesame, which is like the value obtained in the present study. The prominence of fertilizer-related energy in the input structure of industrial hemp can be primarily attributed to the high embodied energy of nitrogenous fertilizers (60.60 MJ kg^{-1}), combined with the relatively high nitrogen requirement of hemp during its rapid vegetative growth phase. This pattern is consistent with the findings of Tang et al. [68], who proved through canopy-scale measurements that hemp exhibits a strong responsiveness of leaf area index and biomass accumulation to nitrogen supply, although its photosynthetic nitrogen-use efficiency (0.3–0.7 mol CO_2 d^{-1} g^{-1} N) is comparable to or higher than that of other C3 crops. The second-largest input was diesel fuel (32.09%; 4392.18 MJ ha^{-1}), which is in line with previously reported values for arable crops grown under semi-arid conditions, where field operations involving primary tillage, sowing, harvesting and transport account for a substantial share of energy consumption [30,33].

The biomass yield of industrial hemp was determined to be 19,870 kg ha^{-1}, and the hemp seed yield was 2150 kg ha^{-1} along with the corresponding energy input, energy output, energy use efficiency, specific energy, energy productivity and net energy were determined as 19,870 kg ha^{-1}, 13,688.51 MJ ha^{-1}, 388,073.80 MJ ha^{-1}, 28.35, 0.62 MJ kg^{-1}, 1.61 kg MJ^{-1} and 374,385.28 MJ ha^{-1}, respectively, for industrial hemp production (Table 4). The energy use efficiency value obtained in the present study (42.28) is markedly higher than the corresponding values reported for many fruit and field crops produced in Türkiye under comparable agronomic conditions, including pecans (3.43) [38], Kaman walnuts (3.39) [28], blackberries (3.97) [43], white cherries (2.31) [39], sesame (2.49) [31], lavender (2.77) [69], and kumquats (0.35) [29]. This pronounced superiority is essentially attributable to the high biomass productivity of industrial hemp per unit area, achieved with a comparatively low total energy input of 12,896.01 MJ ha^{-1}, and to the absence of fungicide and insecticide applications during the growing season—an inherent agronomic advantage of hemp arising from its dense canopy, allelopathic effects, and natural resistance to most major pests and diseases [7,8].

Table 4. Energy use efficiency computations in industrial hemp production.

Calculations	Unit	Values
Industrial hemp biomass	kg ha^{-1}	19,870.00
Hemp seed yield	kg ha^{-1}	2150.00
Energy input	MJ ha^{-1}	13,688.51
Energy output	MJ ha^{-1}	388,073.80
Energy use efficiency	–	28.35
Specific energy	MJ kg^{-1}	0.62
Energy productivity	kg MJ^{-1}	1.61
Net energy	MJ ha^{-1}	374,385.28

The energy performance values reported in the present study are also consistent with the international literature on industrial hemp as a high-yielding bioenergy crop. Prade [70] reported a combustion energy yield of approximately 246 GJ ha^{-1} for autumn-harvested industrial hemp grown under Northern European conditions, while Finnan and Burke [71] determined energy yields of 296 GJ ha^{-1} at autumn harvest for biogas-oriented production systems. Similarly, Kreuger et al. [72] calculated a total energy yield of 171–180 GJ ha^{-1} through the co-production of ethanol and methane from whole-plant hemp biomass. Vávrová et al. [73] emphasized the multipurpose nature of hemp as a feedstock for both bioenergy and biochar production, reporting stem biomass yields of 5.5–8.5 t DM ha^{-1} for adapted European cultivars under Czech conditions. Comparable calorific values, typically in the range of 17.5–19.8 MJ kg^{-1} for hemp straw and whole plants, have been reported in the European literature [69], values broadly comparable to the biomass energy equivalent (27.26 MJ kg^{-1}) adopted in the present study, which additionally captures the energy contribution of seed and inflorescence components. Taken together, these comparisons confirm that industrial hemp ranks among the most energy-efficient annual crops in temperate and semi-arid environments and that the favorable energy balance obtained in the Çumra plain is in line with internationally reported figures.

The input energy in industrial hemp production was further classified into direct energy (DE), indirect energy (IDE), renewable energy (RE) and non-renewable energy (NRE) forms, as presented in Table 5. The respective shares were DE 36.95% (5058.10 MJ ha^{-1}), IDE 63.05% (8630.41 MJ ha^{-1}), RE 10.65% (1458.42 MJ ha^{-1}) and NRE 89.35% (12,230.09 MJ ha^{-1}). The marked dominance of indirect over direct energy reflects the importance of energy embodied in chemical fertilizers and, to a lesser extent, in machinery manufacture, whereas the pronounced predominance of non-renewable over renewable energy mirrors the heavy reliance of the production system on fossil-derived diesel fuel and synthetically produced N–P fertilizers. Similar input-structure patterns have been reported for production in Türkiye by Agızan et al. [74] for oranges, Agızan et al. [75] for wheat, Sarı and Gökdoğan [76] for sour cherries, Kokten et al. [77] for maize, Baran et al. [33] for cotton, and Özbek et al. [37] for lemons, all of which identified non-renewable sources as the dominant component of total input energy. From an agronomic-sustainability perspective, this pattern suggests that the environmental performance of industrial hemp production can be further enhanced by partially replacing mineral nitrogen with biologically fixed nitrogen through legume rotations or green manure, by adopting reduced-tillage soil management to lower diesel consumption, and by gradually increasing the share of renewable energy sources—for example through solar-powered irrigation pumping—in line with the strategies discussed by Lal [23], Burney et al. [24], and Adesina et al. [8].

Table 5. Energy inputs in the types of energy for industrial hemp production.

Energy Groups	Energy Input (MJ ha^{-1})	Ratio (%)
Direct energy	5058.10	36.95
Indirect energy	8630.41	63.05
Total	**13,688.51**	**100.00**
Renewable energy	1458.42	10.65
Non-renewable energy	12,230.09	89.35
Total	**13,688.51**	**100.00**

The total GHG emissions resulting from industrial hemp production were calculated as 590.14 kg CO_2 eq ha^{-1}, with a corresponding GHG ratio of 0.03 kg CO_2 eq kg^{-1} of biomass (Table 6).

Table 6. GHG emissions in industrial hemp production.

Inputs	Unit	GHG Coefficient (kg CO_2 eq $unit^{-1}$)	Input Used per Area (unit ha^{-1})	GHG Emissions (kg CO_2 eq ha^{-1})	Ratio (%)
Tractor and machinery	MJ	0.071	393.11	27.91	4.73
Seed	kg	7.630	25.00	190.75	32.32
Nitrogen (N)	kg	1.300	106.00	137.80	23.35
Phosphorus (P)	kg	0.200	92.00	18.40	3.12
Diesel fuel	L	2.760	78.00	215.28	36.48
Total				**590.14**	**100.00**
GHG ratio (per kg)				**0.03**	

Diesel fuel was identified as the largest contributor to total GHG emissions, with a share of 36.48% (215.28 kg CO_2 eq ha^{-1}), followed by nitrogen fertilizer at 23.35% (137.80 kg CO_2 eq ha^{-1}), tractors and machinery at 4.73% (27.91 kg CO_2 eq ha^{-1}), phosphorus fertilizer at 3.12% (18.40 kg CO_2 eq ha^{-1}), and seeds at 32.32% (190.75 kg CO_2 eq ha^{-1}). The relative composition of emission sources observed in the present study is consistent with the global pattern, in which fossil-fuel combustion in field operations and N_2O fluxes from synthetic nitrogen fertilization jointly account for the major share of GHG emissions in arable cropping systems [23,24,78]. The proportional shares are likewise consistent with the findings of Özbek et al. [43], who reported a 54.55% share of diesel fuel and an 18.07% share of nitrogen in total GHG emissions of blackberry production in Türkiye. The predominance of diesel fuel and nitrogen fertilizer in the energy-input and GHG-emission profiles indicates that these inputs represent the principal intervention points for further improving the environmental performance of industrial hemp production. Diesel consumption could be reduced through conservation or reduced-tillage practices, optimized field-traffic planning, a combination of compatible field operations, and the use of energy-efficient agricultural machinery. Such practices could directly decrease fossil-energy consumption and fuel-related CO_2 emissions while potentially reducing production costs. However, reduced tillage should be adapted to local soil conditions to avoid adverse effects on soil structure, weed management, and crop establishment. The environmental impacts associated with nitrogen fertilizer could be reduced through soil-test-based fertilization, site-specific nutrient management, split nitrogen applications, improved fertilizer timing, and the integration of legumes or green-manure crops into crop rotations. These practices may improve nitrogen-use efficiency and reduce excessive fertilizer application and associated upstream energy requirements and GHG emissions. Nevertheless, reductions in nitrogen inputs should be carefully optimized because insufficient nitrogen availability may restrict canopy development and biomass accumulation, thereby decreasing energy output and potentially increasing GHG emissions per unit of biomass. Therefore, the objective should not be to minimize diesel fuel and fertilizer use independently of crop performance, but rather to optimize these inputs while maintaining high biomass productivity. Combining efficient nutrient management with reduced fuel consumption and renewable-energy technologies, particularly solar-powered irrigation, could further improve the energy balance and carbon efficiency of industrial hemp and enhance its potential as a sustainable alternative crop in the Çumra Plain and similar semi-arid production environments.

The total GHG emissions calculated in the present study (590.14 kg CO_2 eq ha^{-1}) are lower than those reported for several conventional field and orchard crops cultivated under semi-arid Turkish conditions. For example, Özbek et al. [43] calculated 615.26 kg CO_2 eq ha^{-1} for blackberry production, and Karaağaç et al. [60] reported GHG emissions associated with chickpea production in Adana. Similar input–output assessments for various crops in Türkiye have likewise highlighted the dominance of diesel fuel and nitrogen fertilizer as principal emission sources [30,76]. The comparatively low GHG emissions of hemp can be attributed to its limited dependence on plant-protection chemicals, its short growing season, and its capacity to suppress weeds through canopy closure, features that collectively reduce the need for additional field operations and chemical inputs [4,8]. Even more striking is the GHG ratio expressed per unit of yield (0.02 kg CO_2 eq kg^{-1}), which positions industrial hemp among the most carbon-efficient crops in the Central Anatolian context: Özbek et al. [43] reported 0.03 kg CO_2 eq kg^{-1} for blackberries, while life cycle assessment (LCA) studies on industrial hemp by Zampori et al. [79] and González-García et al. [56] have similarly demonstrated low cultivation-stage emissions per unit of biomass. Furthermore, recent LCA studies have shown that, when biogenic carbon uptake is considered, the cultivation of industrial hemp can result in a net-negative carbon footprint at the cradleto-gate level [80]. Although carbon sequestration was beyond the scope of the present input–output analysis, its inclusion in future studies would further strengthen the case for industrial hemp as an environmentally favorable alternative crop within the cropping systems of the Konya Closed Basin. Moreover, the multifunctional use of hemp biomass in fiber, construction, bioenergy, and bio-based product sectors may generate additional sustainability benefits beyond the farm gate, supporting circular bioeconomy strategies and reducing reliance on fossil-derived materials.

Several methodological considerations and limitations should be acknowledged when interpreting the present results. First, the analysis was conducted on a single growing season (2024–2025) and a single experimental site in Çumra; inter-annual variability in precipitation, temperature and yield may modify the magnitude of the energy and emission indicators, although the relative contributions of different input categories are expected to remain comparable. Second, the energy equivalents and GHG emission coefficients used in the calculations were obtained from the international literature; the use of region-specific coefficients, where available, would further improve the accuracy of the results. Third, the present study restricted the system boundary to the field-level production phase and did not include post-harvest operations such as decortication, drying or transport, nor the biogenic carbon sequestered in hemp biomass. Despite these limitations, the high energy use efficiency (28.35), low specific energy (0.62 MJ kg^{-1}) and low GHG ratio (0.03 kg CO_2 eq kg^{-1}) obtained in the present study collectively position industrial hemp as a strong candidate for diversifying cereal-, sugar beet- and maize-dominated rotations in the semi-arid Central Anatolian region.

The production methodology applied in the present study is generally consistent with agronomic practices reported for industrial hemp in other semi-arid and water-limited production environments. Studies conducted under Mediterranean and continental conditions have indicated that appropriate cultivar selection, timely sowing, optimized plant density, balanced nitrogen fertilization, and efficient irrigation management are major determinants of hemp establishment and biomass productivity. Like other semi-arid regions, supplemental irrigation may be required under the conditions of Central Anatolia to prevent water stress during periods of rapid vegetative growth. However, excessive irrigation and nitrogen application may increase energy consumption and environmental impacts without providing proportional increases in biomass yield. Therefore, soil-test-based nutrient management and irrigation scheduling according to crop water requirements are important for maintaining high productivity while improving resource-use efficiency. Comparisons among countries should nevertheless be interpreted cautiously because differences in climate, soil properties, cultivar characteristics, mechanization levels, production objectives, and methodological system boundaries may influence energy-use and GHG-emission indicators. The findings of the present study consequently provide locally derived baseline information while also contributing to the evaluation of hemp production in comparable semi-arid agroecological regions.

Future studies should incorporate direct and indirect soil N_2O emissions together with broader life-cycle assessment components, including post-harvest operations, transportation, and biogenic carbon sequestration, to provide a more comprehensive evaluation of the environmental performance of industrial hemp production. A recent comparative study of the European Union and Gulf Cooperation Council countries reported that improvements in energy efficiency and structural energy policies play a key role in reducing CO_2 emissions, although their effectiveness depends strongly on regional economic and production conditions. The authors emphasized that sustainable decarbonization requires region-specific strategies rather than universal approaches KilinçAta et al. [81].

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The findings of the present study should be interpreted within the scope of the environmental and agronomic conditions under which the experiment was conducted. Since the study was carried out during a single growing season under the semi-arid conditions of Central Anatolia, the reported energy-use efficiency, greenhouse gas emissions, and sustainability indicators are specific to the evaluated production system and should not be generalized to other agroecological regions or climatic conditions. Nevertheless, as industrial hemp cultivation has recently been authorized in this region, these findings provide valuable baseline information regarding the energy and environmental performance of hemp production under local conditions and may support future regional research and production planning. Multi-location and multi-year studies are required to validate these findings under different environmental conditions and management practices.

4. Conclusions

4.1. Energy and Environmental Performance

The present study provided the first comprehensive input–output assessment of energy use efficiency and GHG emissions in industrial hemp (*Cannabis sativa* L.) production in the Çumra district of Konya province, representative of the semi-arid Central Anatolian Region of Türkiye. The main energetic and environmental indicators of hemp production were quantified under field conditions and benchmarked against values reported for other field and orchard crops grown in Türkiye.

The results confirmed that industrial hemp is an exceptionally energy-efficient crop under these conditions, with an energy use efficiency markedly higher than the recent literature values for most field and fruit crops in Türkiye. The input structure was dominated by indirect, non-renewable energy, chiefly synthetic nitrogen fertilizers and diesel fuel, which therefore represent the principal leverage points for improvement. At the same time, GHG emissions, particularly per unit of biomass, were considerably lower than those of conventional crops grown under comparable conditions, placing hemp among the most carbon-efficient crops examined to date in the Turkish context.

4.2. Broader Sustainability Benefits

Beyond the farm-scale energy and emission indicators evaluated in this study, industrial hemp offers broader sustainability benefits that are highly relevant for semi-arid agricultural regions. Its high biomass productivity, low GHG emissions per unit of output, and versatility as a feedstock for fiber, bio-based materials, bioenergy, and other value-added products can contribute to climate change mitigation, resource conservation, and the development of circular bioeconomy value chains. Therefore, wider adoption of industrial hemp may support the transition towards low-carbon and climate-resilient agricultural systems while enhancing the long-term sustainability of farming in water-limited environments.

4.3. Strategies for Improving Sustainability

To further enhance sustainability in the Çumra plain and similar semi-arid environments, the following strategies are recommended: (i) optimizing nitrogen fertilization through soil-test-based application and legume-based green manures or nitrogen-fixing pre-crops; (ii) adopting reduced or conservation tillage to lower diesel consumption and associated emissions; (iii) progressively replacing fossil-derived energy with renewable sources, particularly solar-powered irrigation; and (iv) including biogenic carbon sequestration and post-harvest processing within the system boundary in future life-cycle assessments.

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4.4. Implications for Farmers and Agricultural Planning

Its high biomass productivity, favorable energy balance, and low GHG emissions per unit of biomass indicate that hemp may serve as a resource-efficient diversification option in a region dominated by irrigated cereals, sugar beet, and maize. For farmers, the results provide field-level reference values that may support input optimization through soil-test-based nitrogen management, reduced tillage, efficient field operations, and energy-efficient irrigation. For agricultural planners and policymakers, these findings may contribute to the development of regional crop-diversification strategies, pilot production programs, farmer training, and hemp-based value chains. However, the wider adoption of hemp should also consider local adaptation, water requirements, economic feasibility, market access, and processing capacity. Therefore, hemp should be regarded as a complementary crop that can be gradually integrated into suitable crop rotations rather than as a direct replacement for existing crops.

4.5. Overall Conclusion and Regional Potential

Overall, following its official authorization in Konya province as of the 2024 production year, industrial hemp constitutes a strategically promising alternative crop for Central Anatolia. Its high biomass productivity, low input intensity, favorable energy balance and low carbon footprint per unit of yield support its integration into existing cereal-, sugar-beet- and maize-based rotations and contribute to the diversification, resilience and environmental sustainability of semi-arid cropping systems in Türkiye.

The conclusions of this study are limited to the semi-arid conditions of Central Anatolia and the production system evaluated in this experiment. Therefore, the findings regarding climate-friendly agriculture, carbon efficiency, regional adoption, and crop system resilience should be interpreted as region-specific rather than universally applicable. Further studies conducted across multiple locations, years, and production systems are necessary before broader conclusions regarding the sustainability of industrial hemp production can be drawn.

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