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Evaluating Energy Dynamics: A Comparative Analysis of Pulses Production Systems in Iran

Salman Koocheki[a]

Abstract

This study evaluates energy dynamics in agroecosystems by comparing bean, lentil, irrigated chickpea, and dryland chickpea farms. The analysis focuses on energy efficiency, productivity, benefit-to-cost ratio, and renewable energy use. Data were collected through surveys from farmers cultivating these crops. The results reveal significant differences in energy requirements and input distribution across the examined farms. Direct, indirect, renewable, and non-renewable energy sources contribute differently to each crop, affecting overall energy consumption. Energy use efficiency findings indicate that dryland chickpea is the most efficient, requiring lower energy inputs while yielding higher efficiency. The benefit-to-cost ratio further supports dryland chickpea's economic viability compared to other crops. Among irrigated crops, bean demonstrates superior energy efficiency and profitability. The study suggests that prioritizing dryland chickpea can enhance sustainability by reducing energy consumption while maintaining economic benefits. Additionally, bean presents a viable option among irrigated crops due to its efficiency and profitability. These findings provide valuable insights into optimizing energy use in agriculture, assisting farmers and policymakers in developing strategies for sustainable crop production. By adopting energy-efficient farming practices, agricultural stakeholders can improve productivity while minimizing environmental impacts. The study highlights the need for targeted interventions to enhance renewable energy use and sustainable agricultural practices. Policymakers should consider promoting dryland chickpea cultivation as a strategic option to improve food security while ensuring sustainable resource utilization. Understanding the energy dynamics of different crops allows for more informed decisions, contributing to long-term agricultural sustainability and economic stability.

Keywords: Energy Productivity, pulses production

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1. INTRODUCTION

Pulses, comprising staples in the diet of impoverished rural and urban communities, hold particular significance in developing countries. Concurrently, in developed nations, pulses, including Bean (Phaseolus vulgaris L.), lentil (Lens culinaris L.), and chickpea (Cicer arietinum L.), assume the status of major cash crops. These leguminous varieties, encompassing Bean, lentil, and chickpea, stand out as globally paramount pulses, contributing significantly to both sustenance and economic prosperity. In Iran, the total cultivated area spans approximately 697,000 hectares. Within this agricultural landscape, chickpea, lentil, and bean hold prominent shares, accounting for 61.13%, 21.94%, and 14.26% of the cultivated expanse, respectively. The Khurasan Razavi province in Iran stands as a key pulse-producing region, boasting a substantial cultivating area of approximately 13,500 hectares. Within this province, pulses play a pivotal role, serving as a primary source of raw food materials for numerous rural and urban households. Contemporary agricultural production is heavily dependent on the utilization of non-renewable energies, notably fossil fuels (Erdemir, 2006; Ahmad, 2018). The consumption of fossil energy not only induces direct adverse environmental effects through the emission of CO2 and other combustion byproducts but also contributes to indirect negative impacts on the environment, including the reduction of biodiversity. It is noteworthy that the extensive use of cost-effective fossil energy has far-reaching consequences on the environment, influencing factors such as ecological diversity. The interdependence of energy, economics, and the environment is a well-acknowledged phenomenon (Refsgaard et al., 1998; Pimentel et al., 1994). The intricate relationship among these factors underscores the importance of adopting sustainable practices that balance the needs of agricultural production, economic considerations, and environmental preservation (Ali, 2018; Iqbal, 2018). Furthermore, a closely intertwined relationship exists between agriculture and energy (Ahmad, 2018; Wali, 2018; Muhieddine, 2018). The current productivity and profitability of agricultural practices hinge significantly upon energy consumption. Consequently, the quest for agricultural production methods characterized by enhanced energy productivity remains just as relevant today as it was two decades ago (Refsgaard et al., 1998). The ongoing pursuit of methods that optimize the relationship between energy input and agricultural output underscores the evolving landscape of sustainable and efficient agricultural practices (Yen, 2018; Siddiqi, 2018; Okurut & Mbulawa, 2018). Within agroecosystems, the energy needs are categorically divided into four distinct groups: direct and indirect, non-renewable and renewable. Specifically, direct energy is essential for the execution of numerous tasks, encompassing activities such as land preparation, irrigation, threshing, harvesting, and the transportation of both agricultural inputs and farm products (Singh, 2000; Ali & Audi, 2016; Asif & Simsek, 2018; Iqbal, 2018; Zhang, 2018). This comprehensive classification allows for a nuanced understanding of the diverse energy requirements associated with various facets of agroecosystem management. Indirect energy, as a component within agroecosystems, encompasses the energy expended in the construction, packaging, and transportation of essential elements such as fertilizers, biocides, and machinery (Ozkan et al., 2004; Ali & Rehman, 2015; Maurya, 2018; Ali & Zulfiqar, 2018; Gorus, 2018; Ali & Audi, 2018). This category sheds light on the broader energy footprint associated with the production and distribution of key inputs crucial to agricultural practices, offering a holistic perspective on energy utilization in the agricultural sector. Non-renewable energy within agroecosystems encompasses essential resources such as diesel, chemicals, fertilizers, and machinery, highlighting the dependence on finite and exhaustible sources (Mohammadi et al., 2008; Ali & Zulfiqar, 2018; Hussain, 2018; Ali & Audi, 2018; Wiafe, 2018). In contrast, renewable energy sources in this context include human labor, water, seeds, and farmyard inputs, underscoring the reliance on sustainable and replenishable elements (Mohammadi et al., 2008; Ali & Rehman, 2015; Khan & Ahmad, 2018; Kumar, 2018). This distinction between non-renewable and renewable energy sources provides a critical lens through which to assess the ecological sustainability and resilience of agricultural practices. The widespread utilization of both direct and renewable energy resources not only augments energy supply but also plays a pivotal role in enhancing energy efficiency. This concerted effort holds the potential to make a significant and valuable contribution towards achieving targets for sustainable energy development (Streimikiene et al., 2007; Ali, 2011; Ali et al., 2016; Ali & Naeem, 2017; Khan & Ali, 2018). By prioritizing direct and renewable energy sources, agricultural practices can align with broader sustainability goals, ensuring a more efficient and environmentally conscious approach to energy utilization in the pursuit of long-term energy development objectives. The escalating annual increase in energy consumption within the agricultural sector has raised concerns, particularly as intensified energy use has been linked to significant human health and environmental issues. Recognizing the imperative to address these challenges, there is a pressing need to curtail reliance on fossil energy inputs in agricultural systems. Such a shift holds the potential not only to mitigate adverse impacts on human health and the environment but also to contribute substantially to the reduction of carbon dioxide emissions associated with agricultural practices. Implementing measures to reduce dependence on fossil energy represents a critical step towards fostering sustainable and environmentally responsible agricultural systems.

Indeed, the judicious and effective utilization of energy inputs has emerged as a crucial aspect of sustainable farming (Karimi et al., 2008; Rathke and Diepenbrock, 2006; Ali et al., 2015; Ali, 2015; Mahmood & Aslam, 2018; Ali, 2018). It stands as a fundamental prerequisite for sustainable agriculture, reflecting the imperative to balance agricultural productivity with environmental responsibility. The escalating demand for energy in the agricultural sector is a direct response to population growth, constrained arable land availability, and an increasing desire for elevated standards of living. By prioritizing efficient energy use, agriculture can align itself with the principles of sustainability, fostering practices that are both environmentally conscious and economically viable. The persistent need for escalating food production has led to the intensive utilization of chemical fertilizers, pesticides, agricultural machinery, and other natural resources. Consequently,

[a] Ferdowsi University of Mashhad, Mashhad, Iran

promoting the efficient use of energy in agriculture becomes paramount not only for economic reasons but also as a proactive measure to mitigate environmental issues. By optimizing energy usage, agriculture can play a crucial role in preventing the depletion of natural resources and minimizing the environmental impact associated with intensive agricultural practices. This approach aligns with the overarching goal of fostering sustainable agriculture, where economic productivity is harmonized with environmental stewardship to create a balanced and resilient production system (Erdal et al., 2007; Haider & Ali, 2015; Arshad & Ali, 2016; Ali & Bibi, 2017; Marc & Ali, 2017; Khan, 2018; Sajid & Ali, 2018; Ashraf & Ali, 2018).
The application of input-to-output energy analysis proves instrumental in evaluating the impact of production systems on the environment and gauging the efficiency of energy utilization (Franzluebbers and Francis, 1995). This analytical approach serves as a valuable tool in assessing the intricate relationship between energy inputs and the resulting outputs within various production systems. By scrutinizing this energy balance, researchers and practitioners can gain insights into the environmental implications of different agricultural practices and identify opportunities for enhancing energy efficiency within the broader context of sustainable production. The rate of energy consumption in agriculture is contingent upon a range of environmental factors, including soil quality, climatic conditions, the quantity of inputs utilized, and the specific techniques employed in the production process (FAO, 2005). This acknowledgment underscores the dynamic and multifaceted nature of energy utilization in agriculture, where the interplay of environmental variables and management practices significantly influences the overall energy requirements for productive farming. Understanding and considering these factors are essential for devising strategies that optimize energy use while accounting for the inherent variability in agricultural ecosystems. In developing nations such as Iran, fostering agricultural growth is imperative for nurturing economic development and addressing the increasing demands of a growing population (Ali & Ahmad, 2015; Marc & Ali, 2016; Ali & Audi, 2016; Marc & Ali, 2017; Manzoor & Agha, 2018; Zahid, 2018). Over the last three decades, there has been a noteworthy shift from subsistence farming to commercial farming, marking a transformation in the predominant mode of agricultural production in Iran. This transition underscores the evolving agricultural landscape in response to economic imperatives and the need to sustainably meet the food requirements of a expanding populace. The agricultural sector serves as the second-largest employer in Iran, playing a significant role in contributing to the Gross Domestic Product (GDP). Notably, the share of agriculture in the GDP stood at 10.87%. In response to the global upswing in energy prices in recent years, Iranian entities have proactively implemented measures to curtail fuel and energy consumption. This strategic approach reflects a commitment to resource efficiency and aligns with broader economic considerations, emphasizing the importance of sustainable practices within the Iranian agricultural landscape.
To address the escalating energy demands across all sectors of the economy, Iran has initiated measures such as rationing subsidized petrol and diesel for consumers. Additionally, concerted efforts are underway to enhance the overall efficiency of energy use. These strategies are crucial in mitigating the increasing strain on energy resources. Importantly, there is a growing awareness among the populace regarding the implications of these policies on energy usage in Iran. This heightened awareness reflects a broader understanding of the need for responsible energy management and its impact on both the economy and the environment. Numerous studies have delved into comprehensive analyses, encompassing input and output energy evaluations, along with economic assessments, to ascertain the energy efficiency of diverse crop productions. Notable examples include investigations into chickpea, irrigated and dryland wheat, barley in Iran, dry bean, and canola in Turkey (Ozkan et al., 2004). Additionally, research has been conducted on rice in Malaysia (Bockari Gevao et al., 2005) and maize and sorghum in the United States (Mohammadi et al., 2008). These studies provide valuable insights into the intricate relationship between energy inputs, crop yields, and economic factors, contributing to a nuanced understanding of sustainable and efficient agricultural practices across different regions. The absence of published studies on the energy and economic analysis of pulse production in Iran underscores a notable gap in the existing literature. Given the global significance of pulses for both food and feed, a comprehensive understanding of the energy consumption associated with their production is imperative. The lack of such studies hinders efforts to enhance energy use efficiency in pulse production systems. Exploring and documenting the energy dynamics and economic aspects of pulse cultivation in Iran would not only contribute valuable insights to the scientific community but also aid in the development of informed and sustainable agricultural practices specific to pulse crops in the region.

2. MATERIAL AND METHODS

The present study was conducted in Khorasan Razavi province which is located northeast of Iran, within 30024 and 38017 north latitude and 55017 and 61015 east longitude. Total area of the province is 12842000 ha and the total farming area of bean, lentil and chickpea is 13486 ha consisting of 916 ha bean, 2245 ha lentil, 2108 ha irrigated chickpea and 8217 ha dryland chickpea. In order to determine the relation between pulse yield and energy consumption, required data were collected from growers by using a face to face questionnaire. In addition to the data obtained by surveys, previous studies of related organizations such as Food and Agricultural Organization (FAO) and Ministry of Agriculture of Iran (MAJ) were also utilized during this study. The number of operations involved in the pulse production systems, and their energy requirements influence the final energy balance. The evaluation of energy efficiency in the agricultural system was conducted using the energy ratio, calculated as the relationship between output and input, as outlined by Alam et al. (2005). This energy ratio serves as a key metric for assessing the effectiveness of energy utilization within the agricultural production processes under study. By quantifying the ratio of output to input energy, researchers can gain valuable insights into the overall efficiency and sustainability of the agricultural systems being analyzed. Human labor, machinery, diesel oil, fertilizer, pesticides and seed amounts and output yield values of bean, lentil, irrigated chickpea and dryland chickpea have been used to estimate the energy ratio. Energy equivalents shown in Table 1 were used for estimation. The sources of mechanical energy used on the selected farms included tractors and diesel oil. The mechanical energy was computed on the basis of total fuel consumption (l ha^{-1}) in different farm operations. To quantify the energy consumed in the agricultural operations, conversion factors were applied, and the results were expressed in megajoules per hectare (MJ ha^{-1}), following the methodology described by Tsatsarelis (1991). This conversion allowed for a standardized and comparable measure of energy consumption across different inputs and processes involved in the cultivation of bean, lentil, irrigated chickpea, and dryland chickpea. Expressing the energy consumption in MJ ha^{-1} provides a common unit of measurement, facilitating the analysis and comparison of energy use efficiency in the studied pulse production systems.
The study compiled fundamental data regarding energy inputs and crop yields for bean, lentil, irrigated chickpea, and dryland chickpea, transferring this information into Excel spreadsheets. Subsequently, the dataset underwent analysis using the SPSS program. Key energy-related metrics, including energy use efficiency, energy productivity, specific energy, and net energy, were computed based on established input and output energy equivalents, drawing upon the methodology outlined by Bockari Gevao et al. (2005). These calculated metrics provide a robust framework for assessing and comparing the energy dynamics and efficiency of the different pulse production systems under investigation. In the energy analysis of pulse production, indirect energy encompasses the energy embedded in various inputs such as seeds, chemical fertilizers (NPK), herbicides (Treflan and Basagran), pesticides (Diazinon), fungicides (Carboxin), and machinery. On the other hand, direct energy factors in human labor, diesel, electricity, and water utilized during pulse cultivation. Non-renewable energy sources include diesel, electricity, chemical pesticides, chemical fertilizers, and machinery, while renewable energy comprises human labor, seeds, and water. This detailed categorization allows for a thorough examination of the diverse energy components involved in pulse production, distinguishing between indirect and direct sources as well as non-renewable and renewable elements. In the economic analysis of pulse production systems, economic inputs primarily encompass variable costs. These variable costs of production comprise current expenses such as chemicals, fuel, human labor, and electricity. On the economic output side, pulse production systems account for both grain and straw yields. This consideration of variable costs and the dual nature of economic output provides a comprehensive framework for

evaluating the economic viability and efficiency of pulse cultivation. The inclusion of variable costs and output components like grain and straw yield ensures a thorough assessment of the economic aspects associated with pulse production.

3. RESULTS AND DISCUSSION

The data presented in Table 1 highlights the energy consumption profile of bean cultivation in Iran by examining a range of inputs and their associated energy equivalents per hectare. This micro-level analysis reveals the energetic composition of the production system and allows for insight into where the greatest energy investments are made, as well as how these investments are distributed across various sources. Evaluating energy consumption in this manner offers a clearer understanding of both the efficiency and sustainability of agricultural practices related to pulses, which are increasingly important in addressing both food security and environmental concerns. The most prominent feature of the input structure is the extraordinary energy demand associated with water for irrigation and electricity. Water accounts for 30.32% of the total energy input, with 6783.87 megajoules per hectare. This is complemented by electricity, which contributes 4923.47 megajoules and 22.64% of total energy. Combined, these two inputs constitute more than half of the total energy invested in bean farming. These findings strongly suggest that irrigation in Iranian bean agriculture is both energy-intensive and likely dependent on mechanized pumping systems, particularly in regions facing water scarcity or low groundwater levels. Similar studies conducted in arid or semi-arid agricultural zones have revealed comparable patterns, where irrigation often dominates the energy profile due to inefficiencies in water management systems and outdated irrigation technologies (Mandal et al., 2002). This high dependency on irrigation also underscores the vulnerability of the system to energy price fluctuations and water availability, raising concerns about long-term sustainability.

Diesel fuel represents the third-largest energy input, contributing 3903.82 megajoules per hectare or 16.28% of total energy use. This figure highlights the central role of mechanized farming operations such as land preparation, planting, and harvesting in the bean production system. Despite the moderate machinery energy figure of 1487.54 megajoules (6.14%), the diesel usage figure suggests that the machinery employed may be older or less fuel-efficient, which tends to consume more diesel for operational tasks. These insights align with broader findings in mechanized agricultural systems, particularly in developing contexts, where operational inefficiency drives up fossil fuel use and ultimately inflates both economic and environmental costs (Ozkan et al., 2004). Another notable input is nitrogen fertilizer, which accounts for 6.65% of the total energy input, equivalent to 1723.19 megajoules per hectare. While nitrogen is essential for plant growth, especially in leguminous crops like beans that benefit from nitrogen fixation, the relatively moderate percentage here may reflect balanced fertilizer management or the inherent ability of legumes to utilize atmospheric nitrogen through symbiotic bacteria. Comparatively, phosphate input is slightly lower at 5.47% of total energy. The moderate use of chemical fertilizers indicates an attempt to balance nutrient supply with energy conservation. However, even moderate fertilizer use contributes significantly to indirect energy consumption, particularly due to the energy-intensive nature of fertilizer manufacturing. This pattern has been documented in multiple life-cycle analyses of agricultural systems, particularly in crops with relatively high biomass yields (Pimentel & Pimentel, 2008).

Human labor, contributing only 988.59 megajoules (3.98%), reflects the shift away from traditional labor-intensive farming toward mechanization in bean production. In many regions, particularly those with low labor availability or high labor costs, the reduction in labor input is a consistent trend, replaced by higher energy input through fuel and machinery. However, labor efficiency in energy terms remains a critical metric for comparing traditional versus modern agricultural practices. Lower human labor energy input does not necessarily equate to increased overall efficiency if it leads to a disproportionate rise in mechanical and chemical inputs (Singh et al., 2003). The relatively minor inputs—fungicide (0.41%) and seed energy (4.41%)—further characterize the input structure as focused more on operational inputs than biochemical or biological ones. This suggests that pest management is not a major energy sink in the current bean production system or that it is managed using low-dose applications. Seed energy, on the other hand, is in line with expectations for an annual leguminous crop, as seed weight is relatively high and contributes to the total energy requirement during sowing.

Moving to outputs, the energy output from bean grain yield stands at 16879.83 megajoules per hectare, representing 40.51% of the total output energy. However, the output energy from bean straw is even greater, reaching 22440.71 megajoules and accounting for 59.88% of the total output energy. This means that while the grain is the primary economic product, the straw provides a substantial share of energy output, possibly due to its secondary uses in fodder, bioenergy, or organic matter recycling. The high straw-to-grain ratio reflects a dual-purpose crop strategy, maximizing biomass utility. This dual-output system is vital in sustainability analyses, particularly in resource-constrained agricultural settings where by-products play a major role in supporting the broader agricultural ecosystem (Alam et al., 2005). The dominance of irrigation, electricity, and diesel as energy inputs, contrasted with the high-energy return from both grain and straw, paints a mixed picture of the energy efficiency of bean production in this context. While output energy is high, the process remains dependent on energy-intensive inputs, some of which (like water and electricity) may become increasingly constrained under climate change or infrastructure degradation. This calls for a reevaluation of input technologies and practices. Investments in drip or sprinkler irrigation systems, solar-powered water pumps, and improved fuel efficiency for machinery could significantly lower the energy input burden without compromising output. Furthermore, energy audits of this nature contribute to developing energy productivity indicators and energy ratios such as energy use efficiency and net energy gain, which are essential for guiding policy toward low-carbon agriculture. A system where more than 50% of the energy inputs are concentrated in water and electricity suggests the need for integrated resource planning that addresses both water and energy sustainability in a single framework.

Table 1: Energies consumed in bean farms

Input	Quantity per unit area (ha)	Total energy equivalent (MJ)	Percentage of total energy input
Human labor	561.65	988.59	3.98
Machinery	24.53	1487.54	6.14
Diesel fuel	86.66	3903.82	16.28
Nitrogen	24.11	1723.19	6.65
Phosphate (P2O5)	86.08	1301.31	5.47
Fungicide	0.53	81.9	0.41
Electricity	1340.47	4923.47	22.64
Water for irrigation	6700.64	6783.87	30.32
Seed	65.88	926.99	4.41
Bean grain yield	1333.29	16879.83	40.51
Bean straw yield	2171.52	22440.71	59.88

The energy consumption profile of lentil farms in Iran, as outlined in Table 2, provides a comprehensive breakdown of input contributions in terms of quantity and energy equivalents, thereby allowing for a detailed understanding of the energy dynamics underlying this legume production system. This energy audit, similar in structure to that used for bean production, reveals some critical shifts in input priorities and output patterns, with implications for resource management, cost-efficiency, and sustainability in agricultural practice. The focus on lentils—a key protein source and nitrogen-fixing crop—underscores the relevance of such evaluations in the context of both environmental stewardship and food security. In the case of lentils, diesel fuel emerges as the most significant single contributor to total energy input, accounting for 26.61% of the total or 3304.87 megajoules per hectare. This proportion suggests a heavy reliance on mechanized farm operations for tasks such as soil preparation, sowing, and harvesting. The relatively high diesel input compared to machinery energy (1379.15 MJ, 8.99%) may reflect inefficiencies in fuel use or the use of outdated machinery requiring more energy to operate. Such patterns have been widely reported in energy-intensive farming systems in semi-arid regions, where over-mechanization without concurrent technological upgrades often results in inflated fossil fuel consumption (Adewale et al., 2016). Given the growing concern over fuel cost volatility and environmental impact, this level of diesel dependency in lentil farming signals the need for policy interventions encouraging energy-efficient machinery and precision farming practices.

Irrigation represents the second-largest source of energy expenditure in lentil farms, with water for irrigation requiring 2469.8 megajoules per hectare, making up 19% of the total energy input. Electricity usage, primarily for pumping water, contributes a further 1990.05 megajoules (13.4%). Combined, these irrigation-related inputs constitute over 32% of total energy use, reflecting a substantial energy burden tied to water resource management. Unlike bean production, where water and electricity accounted for more than half of total energy use, lentil production appears slightly less water-dependent, likely due to its relatively drought-tolerant characteristics. Nonetheless, these inputs remain substantial, indicating that water use efficiency is a critical factor in improving the energy profile of lentil agriculture. The correlation between irrigation energy and total energy use underscores the potential benefits of improved irrigation systems such as drip or sprinkler mechanisms, which have been shown to significantly reduce energy and water consumption in dryland farming contexts (Yilmaz et al., 2005). Nitrogen fertilizer contributes 1588.78 megajoules per hectare (13.46%), followed by phosphate at 558.8 megajoules (4.5%) and potassium at 264.88 megajoules (1.79%). While lentils are leguminous and capable of biological nitrogen fixation, the application of synthetic nitrogen is often necessary to supplement soil deficiencies and ensure optimum yields. However, the relatively high nitrogen input raises questions about the balance between natural fixation and artificial supplementation, particularly when viewed through the lens of energy use. This is a notable consideration because the production of nitrogen fertilizer is among the most energy-intensive processes in modern agriculture. The disproportionately high energy cost of nitrogen inputs has been widely recognized in studies assessing the energy efficiency of legume crops, with scholars advocating for a more integrated soil fertility management approach to minimize external nitrogen dependence (Zhou et al., 2014).

The remaining chemical inputs—herbicides, pesticides, and fungicides—together contribute a modest 498.23 megajoules or approximately 3.91% of the total energy input. This low proportion reflects the generally lower chemical input requirements of lentil crops compared to cereals or high-yield commercial vegetables. The inherent resistance of lentils to common pests and diseases may reduce the need for frequent chemical applications, which not only conserves energy but also supports environmental and soil health. However, the relatively modest application does not negate the importance of integrated pest management strategies, especially under changing climatic conditions that may alter pest dynamics and necessitate more energy-demanding interventions over time (Mousavi-Avval et al., 2011). Seed energy input accounts for 799.19 megajoules per hectare (6.18%), which is consistent with expectations for a crop like lentil that is seeded at moderate densities. Human labor, contributing 823.22 megajoules (6.41%), plays a slightly more prominent role here than in bean production. This may reflect variations in labor requirements due to differences in crop management practices or terrain conditions. The labor component, although relatively modest, remains significant in the broader context of sustainable agriculture, where optimizing the labor-to-mechanization ratio can yield both economic and energy-use benefits.

Table 2: Energies consumed in lentil farms

Input	Quantity per unit area (ha)	Total energy equivalent (MJ)	Percentage of total energy input
Human Labor	404.55	823.22	6.41
Machinery	19.05	1379.15	8.99
Diesel fuel	68.83	3304.87	26.61
Nitrogen	24.57	1588.78	13.46
Phosphate (P2O5)	49.82	558.8	4.5
Potassium (K2O)	26.06	264.88	1.79
Herbicides	1.08	220.24	1.72
Pesticide	1.91	194.94	1.51
Fungicide	0.54	83.05	0.68
Electricity	570.59	1990.05	13.4
Water for irrigation	2444.12	2469.8	19
Seed	54.57	799.19	6.18
Bean grain yield	757.2	9945.29	43.07
Lentil straw yield	1242.42	15151.31	63.91

The output energy profile shows lentil straw yielding 15151.31 megajoules per hectare (63.91%), while grain yield accounts for 9945.29 megajoules (43.07%). These outputs clearly indicate a highly productive system in terms of biomass, with straw forming the larger share. In agronomic systems where straw is utilized for fodder, compost, or even bioenergy production, this high straw yield is not merely a by-product but a valuable co-output contributing to the circularity and energy efficiency of the system. This dual-use characteristic of lentil crops strengthens their sustainability profile, especially in integrated crop-livestock systems where straw supports animal husbandry (Singh et al., 2007). However, when comparing the input-output structure, lentil production appears to be slightly more energy-intensive than bean production in terms of diesel and nitrogen inputs, while offering relatively higher returns in straw energy output. This may be due to differences in cropping cycles, climatic adaptability, or soil management practices between the two systems. The higher energy allocation to diesel and irrigation for lentils suggests that these farms may be operating in regions with less favorable climatic conditions or less efficient farming infrastructure. This finding aligns with research on pulse production in arid zones, where even leguminous crops with low water needs often require substantial external energy inputs to maintain productivity under stress conditions (Zangeneh et al., 2010). The results

underscore the importance of targeted technological and policy interventions aimed at improving energy use efficiency in lentil farming. Recommendations include promoting fuel-efficient machinery, precision fertilizer application, renewable energy sources for irrigation, and better integration of biological nitrogen fixation practices. In regions where lentil is a staple or significant cash crop, such measures could substantially reduce energy costs and environmental impact while maintaining or even enhancing yields. Moreover, these insights support the argument for energy-based agricultural planning, wherein energy audits become essential tools for assessing the viability and sustainability of crop systems. The data provided for lentils indicate that while the crop offers robust biomass output and relatively moderate chemical input needs, inefficiencies in fuel and irrigation remain key barriers to improving the overall energy balance. Continued research and investment into energy-smart agriculture will be necessary to overcome these challenges and to secure food-energy nexus goals in water-stressed regions.
The comparative energy analysis between irrigated and dryland chickpea farms reveals critical insights into the resource demands and structural efficiencies of each production system. Table 3 represents the energy input breakdown in irrigated chickpea cultivation, while Table 4 outlines the corresponding values for dryland chickpea farming. Together, these tables allow for a nuanced understanding of how water access and farming systems influence energy consumption, input allocation, and output generation, offering essential information for sustainable agricultural planning in semi-arid regions such as those commonly found in Iran. Irrigated chickpea farms rely heavily on diesel fuel, which contributes 3978.65 megajoules per hectare or 24.75% of the total energy input. Diesel serves as a proxy for mechanization and transportation-related activities, and its dominance reflects the mechanized nature of field preparation, irrigation pumping, and harvesting processes. Diesel energy consumption is relatively high compared to other inputs, underscoring its centrality in irrigated agriculture. However, its reliance on fossil fuels raises questions about long-term cost and environmental sustainability. This finding aligns with studies that emphasize how mechanization in irrigated systems tends to elevate diesel usage due to increased farm operations, particularly in fuel-intensive tillage and water management (Singh et al., 2007). Electricity is the second-largest energy input in irrigated chickpea farming at 2371.45 megajoules per hectare (14.73%), suggesting the use of electric pumps for water extraction or distribution. Together with diesel, these two energy sources account for nearly 40% of the energy input, highlighting the energy-intensive nature of irrigation in chickpea production. These figures point to a structural dependency on both fossil fuels and electricity in supporting water-intensive cropping practices. Such dependency could be mitigated through renewable-powered irrigation systems, which are increasingly recommended in arid regions to lower operational costs and carbon footprints (Panwar et al., 2011).
Fertilizer inputs also represent a substantial portion of total energy use. Nitrogen fertilizer accounts for 1900.67 megajoules (11.4%), phosphate for 542.71 megajoules (3.49%), and potassium for 274.77 megajoules (1.62%). The high energy equivalent of nitrogen, compared to phosphate and potassium, is expected given the energy-intensive process required to synthesize nitrogen fertilizers. Despite chickpeas being a leguminous crop capable of nitrogen fixation, supplemental nitrogen is often applied to boost early growth and yield stability, especially in irrigated systems. The heavy reliance on external nutrient inputs in irrigated chickpea systems reflects a tendency toward intensive cultivation practices, which may boost yields but also contribute to input-driven energy inflation (Houshyar et al., 2012). Pesticide and fungicide inputs together account for only 1.87% of the energy input, while herbicides contribute 1.39%. These inputs play a minimal role in overall energy use, which may be due to the chickpea plant's inherent resistance to many pests or to targeted pesticide use. However, their presence suggests some level of input intensification, typical of irrigated farming systems where higher plant density and biomass can increase disease susceptibility and weed pressure. Energy conservation efforts could explore integrated pest management strategies to reduce even this small but non-negligible share of chemically derived energy.
Human labor in irrigated systems contributes 772.21 megajoules (4.99%), while machinery adds another 1375.01 megajoules (9.09%). These inputs highlight a mechanized but still labor-supported system. The energy share from human labor is moderate, indicative of labor mechanization yet retaining some manual operations for planting, maintenance, or harvesting. This distribution reflects a transitionary farming model where mechanization is dominant but labor is still an essential component, particularly in regions with semi-skilled agricultural workforces. In stark contrast, dryland chickpea farms exhibit a significantly different energy profile. Diesel fuel is the dominant input at 1417.94 megajoules per hectare, accounting for 51.88% of total energy input. This figure is remarkably higher than in irrigated farms, suggesting that, despite reduced input diversity, the few operations in dryland systems are highly diesel-dependent. The lack of irrigation reduces the need for electricity, fertilizers, and associated machinery, concentrating the energy burden primarily in fuel-based mechanization. The absence of water-related energy use shifts the structure from a multi-input model to one dominated by direct energy use. This is consistent with findings in other dryland systems, where energy use is concentrated in fuel-intensive processes due to limited reliance on irrigation and synthetic inputs (Ozkan et al., 2004).

Table 3: Energies consumed in irrigated chickpea farms

Input	Quantity per unit area (ha)	Total energy equivalent (MJ)	Percentage of total energy input
Human Labor	441.65	772.21	4.99
Machinery	21.33	1375.01	9.09
Diesel fuel	79.93	3978.65	24.75
Nitrogen	24.1	1900.67	11.4
Phosphate (P2O5)	41.65	542.71	3.49
Potassium (K2O)	24.73	274.77	1.62
Herbicides	0.99	231.14	1.39
Pesticide	2.19	197.99	1.24
Fungicide	0.47	95.52	0.63
Electricity	752.58	2371.45	14.73

Machinery contributes 605.08 megajoules (20.32%) in dryland farms, which, though lower in absolute terms than in irrigated farms, represents a higher proportion of the total input energy due to the overall lower energy input structure. Similarly, human labor accounts for 190.61 megajoules (7.96%), indicating a slightly greater reliance on manual work relative to the total energy used. This is often characteristic of dryland systems, where resource constraints limit mechanization and input diversity, necessitating greater human involvement in weed control and post-harvest processing (Mohammadi et al., 2008). Chemical input use in dryland systems is minimal. Herbicide use represents 179.16 megajoules (6.72%), while no fertilizers, pesticides, or fungicides are reported. The absence of fertilizer inputs suggests an organic or low-input cultivation method, which, although more energy-efficient, may pose challenges for yield stability and nutrient depletion. The reliance on herbicides indicates an area where integrated weed management could potentially reduce energy inputs further while maintaining crop productivity. Regarding output, dryland chickpea farms produce 2335.41 megajoules from grain yield (30.16%) and 5230.1 megajoules from straw yield (75.06%). The high proportion of energy from straw emphasizes the importance of crop residue in the output energy equation. This could be due to its use as livestock feed, soil amendment, or even as a source of bioenergy. The greater output from straw relative to grain suggests that dryland systems may be optimized more for total biomass than for seed yield, especially in marginal lands. This observation mirrors findings from energy audits of dryland pulse systems in low-rainfall zones, where by-product utilization compensates for lower grain output (Singh et al., 2004). Overall, the comparison reveals that irrigated chickpea farming is more diverse in terms of energy input sources, with significant contributions from electricity, fertilizers, and a broader range of agrochemicals. This system provides more input flexibility and potentially higher yields but at a higher energy and economic cost. Dryland chickpea production, while more energy-efficient in structure, depends heavily on diesel and produces a higher proportion of energy in the form of straw. The energy use patterns in both systems reflect broader strategic trade-offs between intensification and resource conservation. From a sustainability standpoint, the irrigated system may benefit from technological interventions aimed at reducing water and fertilizer-related energy use, while dryland systems could focus on optimizing mechanization efficiency and enhancing soil nutrient management through organic means.

Table 4: Energies consumed in dryland chickpea farms

Input	Quantity per unit area (ha)	Total energy equivalent (MJ)	Percentage of total energy input
Human Labor	96.67	190.61	7.96
Machinery	8.26	605.08	20.32
Diesel fuel	26.22	1417.94	51.88
Herbicides	0.98	179.16	6.72
Chickpea grain yield	135.76	2335.41	30.16
Chickpea straw yield	375.49	5230.1	75.06

4. CONCLUSIONS

The primary objective of this study was to conduct an energy input-output analysis of pulse production systems employed by Iranian farmers. This analysis aimed to comprehensively assess the energy dynamics involved in the cultivation of pulses, providing insights into the efficiency and sustainability of these agricultural practices. By scrutinizing the input and output energy components, the study sought to contribute valuable information for the development of informed and resource-efficient agricultural strategies in the context of pulse production in Iran. The findings of the study reveal that diesel fuel, water for irrigation, machinery, and electricity were the predominant components of energy inputs in irrigated farms. The elevated consumption of diesel fuel is attributed to the intensive utilization of machinery for various operations, including soil preparation, cultural practices, harvest, and transportation. This insight into the major contributors to energy inputs underscores the significance of these resources in irrigated pulse production systems, highlighting areas where targeted interventions for efficiency and sustainability can be implemented. The observed pattern may be influenced by the relatively small average size of pulse farms. However, the study's results suggest that water for irrigation was not utilized efficiently in the examined farms. This inefficiency appears to stem from the application of unsuitable irrigation methods by farmers, deviating from scientific principles. Addressing and improving irrigation practices in line with scientific guidelines could be a crucial avenue for enhancing water use efficiency in pulse farming, contributing to both environmental sustainability and the economic viability of agricultural operations. Achieving minimal production with high energy efficiency is increasingly vital in the current market scenario, where crop prices are rising rapidly, and predictions suggest further increases in the future. This becomes essential for governments and policymakers to prevent the development of a vulnerable food market and safeguard the well-being of low-income individuals. Striking a balance between efficient agricultural practices and food production is crucial for ensuring both economic stability and accessibility to essential food resources, especially for those with limited financial means. Hence, there is a pressing need for the adoption of a new policy encouraging farmers to embrace energy-efficient practices that enhance crop yields without depleting natural resources. The outcomes of the current study emphasize that, among the studied crops, dryland chickpea exhibited the highest efficiency in terms of energy utilization. This underscores the potential benefits of promoting and incentivizing energy-efficient approaches in agriculture to ensure sustainable and resilient food production systems. A strategic shift towards such practices can contribute significantly to both agricultural productivity and the conservation of vital natural resources. Dryland farming in Iran presents additional positive aspects, including the reduction of erosion through soil coverage and minimal or no consumption of biocides and synthetic fertilizers. These factors contribute to lower energy input requirements and establish more environmentally friendly production systems. Among the irrigated crops studied, bean demonstrated the highest efficiency in both energy and economic benefits. This suggests that promoting the cultivation of beans, particularly in irrigated systems, could offer a favorable balance between energy efficiency and economic returns, aligning with sustainable and environmentally conscious agricultural practices.

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