Energetic and Economic Evaluation of Olive Production Systems: A Comparative Assessment of Chemical, Mechanical, and Integrated Weed Management Strategies

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Abstract

This study evaluates the energy consumption and economic performance of three different weed control methods employed in olive orchards in Tarom County, Zanjan Province, Iran, with an emphasis on sustainable agriculture. The objective is to assess the energy efficiency and cost-effectiveness of different weed management systems. The analysis includes chemical weed control (System I), mechanical control (System II), and integrated weed management (System III). Data were collected through interviews with 50 olive farmers, supplemented by official agricultural records. Results show that total energy consumption was highest in System III (93,069.16 MJ ha^{-1}), and lowest in System I (64,297.16 MJ ha^{-1}). System I also demonstrated superior energy efficiency (0.74), output energy (47,648.40 MJ ha^{-1}), and energy productivity (0.06 kg MJ^{-1}), making it the most viable option for optimizing energy consumption. Economically, System I generated the highest net profit (4,662.28 $ ha^{-1}) and benefit-cost ratio (2.66), outperforming Systems II (3,073.31 $ ha^{-1}; BCR: 2.16) and III (2,953.57 $ ha^{-1}; BCR: 1.97). The study concludes that System I, with its efficient use of renewable energy, is the most viable option in terms of both energy and economic performance, providing a balance between low energy input and high yield, thus maximizing profits and minimizing production costs. These findings emphasize the importance of selecting appropriate weed control methods to optimize energy use and reduce overall production costs in olive cultivation.

Keywords: Affordability, Efficiency, Energy, Sustainability, Weeds

Introduction

The olive tree (*Olea europaea* L.), one of the oldest fruit-bearing species in the Oleaceae family, holds a prominent place in the history of human agriculture. Archaeological evidence traces its domestication to the eastern Mediterranean basin, where wild populations were first cultivated by humans millennia ago. Today, olive cultivation thrives across southern Europe, North Africa, and the Middle East, symbolizing the enduring relationship between humanity and nature (Langgut *et al.*, 2019; Valamoti, Gkatzogia, & Ntinou, 2018).

Since the advent of agriculture, one of the primary challenges faced by farmers has been the presence of non-target plants, commonly known as weeds. This co-evolutionary relationship between humans and weeds dates back to the origins of agriculture itself. The widespread adoption of monoculture practices and globalization of major crops has further exacerbated the need for effective weed control. It is important to note that these weeds are, for the most part, taxonomically identifiable species (Clements & Jones, 2021).

Weeds possess a high degree of phenotypic plasticity, enabling them to thrive in a wide range of habitats. This adaptability is further exacerbated by the ongoing anthropogenic climate crisis, which is altering global climatic patterns and ecological niches. The 20th century marked a pivotal era in weed science, characterized by the development and widespread adoption of synthetic herbicides (Clements & Jones, 2021). Despite ongoing research and evaluation of alternative weed control methods, such as herbicide application with diverse chemical structures, mechanical systems like mowing and plowing, mulching, manual weeding, crop rotation, and others, herbicides remain the predominant tool for weed management in global agriculture. This reliance is driven by factors including large-scale monoculture farming, economic considerations, and the pursuit of high agricultural efficiency (McErlich & Boydston, 2014). Although herbicides offer several benefits, their extensive application has encountered numerous challenges. These include substantial economic expenditures, high energy consumption, environmental damage (Zhang, Jiang, & Ou, 2011), the development of herbicide-resistant weed populations (Beckie, 2006; Egan, Maxwell, Mortensen, Ryan, & Smith, 2011; Powles & Yu, 2010), and the potential risks associated with chemical residue accumulation in cultivated crops.

Driven by the expansion of mechanization and increased input usage, particularly in developing countries shifting from traditional to mechanized farming, the agricultural sector's escalating energy dependence results in substantial consumption and considerable costs associated with chemical compounds (herbicides, pesticides, and fertilizers), fossil fuels, and electricity (Khan & Hanjra, 2009; Soleymani, Asakereh, & Safaieenejad, 2025). Conventional, intensive agriculture is characterized by high energy consumption and costs due to the application of synthetic inputs such as herbicides, pesticides, and fertilizers, as well as the implementation of advanced technologies. Consequently, there is a pressing need for innovative agricultural practices and weed control systems that prioritize sustainability across multiple dimensions, including environmental, economic, social, technical, and health considerations. To augment production and eco-efficiency, it is imperative to optimize the productivity of production factors and implement suitable systems (Nikkhah, Khojastehpour, Emadi, Taheri-Rad, & Khorramdel, 2015). Conversely, to facilitate informed decision-making in the development of energy-efficient and economically viable agricultural practices, the implementation of comprehensive evaluation tools is necessary to assess the multifaceted energy and economic implications of diverse farming methods (Kulak, Nemecek, Frossard, Chable, & Gaillard, 2015; Settanni, Notarnicola, & Tassielli, 2010). A variety of methodologies are employed to evaluate the energy consumption and economic performance of agricultural crops cultivated in fields and orchards (Schröder, Aarts, Ten Berge, Van Keulen, & Neeteson, 2003), Nevertheless, crop production necessitates a suitable methodology for assessing and analyzing energy consumption and economic performance across various activities. Additionally, the implementation of systems to reduce costs and optimize energy usage is crucial (Mousavi-Avval *et al.*, 2017; Rahmani, Parashkoohi, & Zamani, 2022).

The energy ratio, which measures energy efficiency, is calculated as the ratio of output energy (e.g., energy in the harvested crop) to input energy (e.g., energy used in cultivation). This ratio depends on the production methods and inputs employed. By optimizing the energy ratio, it is possible to enhance production stability, improve economic efficiency, conserve fossil fuel resources, and reduce environmental impacts such as air pollution (Yousefi, Damghani, & Khoramivafa, 2014).

Economic analysis serves as a crucial tool for evaluating alternative approaches and selecting those that optimize labor utilization, minimize time expenditure, and reduce costs. This methodology entails a comparative assessment of the costs associated with each option against the anticipated overall benefits (Azizi & Heidari, 2013). By meticulously examining the ramifications of different production systems on energy consumption and environmental impact, policymakers can formulate well-informed strategies that foster sustainable practices across various agricultural sectors (Rigamonti, Grosso, & Giugliano, 2009).

Developing and underdeveloped economies possess considerable potential for the expansion and development of horticultural production. The horticultural industry is a significant consumer of energy and materials, owing to its reliance on agricultural machinery, irrigation systems, agrochemical agents, transportation, and fossil fuels. Hence, the reduction of energy consumption in horticultural production can serve as a cornerstone for achieving sustainable productivity and economic efficiency. To this end, agricultural producers should integrate energy efficiency considerations into their production planning and management practices (Ozkan, Akcaoz, & Fert, 2004a; Ozkan, Kurklu, & Akcaoz, 2004b).

Iran, endowed with diverse climatic and microclimatic conditions, offers an exceptionally suitable environment for olive cultivation (Azimi, Zeinanloo, & Mostafavi, 2016). This natural advantage has positioned the country as the nineteenth-largest global producer of olives. According to the Food and Agriculture Organization of the United Nations (FAO, 2024), olive trees covered 24,397 hectares of Iranian land in 2022, yielding a substantial harvest of 114,599.87 metric tons. Notably, Zanjan Province emerges as Iran's foremost olive-producing region, contributing over 40% of the nation's total output (MAJ, 2024). These achievements not only underscore the olive tree's adaptability to Iran's diverse ecosystems but also highlight the country's vast potential for sustainable agricultural development.

A variety of methods are employed to eradicate weeds in olive orchards, encompassing both physical and chemical approaches. Physical methods include mechanical removal, tillage, hand weeding, and mulching, while chemical control relies on the application of herbicides (Cirujeda *et al.*, 2024; MacLaren, Storkey, Menegat, Metcalfe, & Dehnen-Schmutz, 2020). Balancing the demands of system stability, economic viability, and energy efficiency is essential for successful weed control strategies. A rigorous examination of diverse weed control systems in olive orchards is essential. The aim is to identify the system that promotes stability, reduces costs, and minimizes energy input in olive production (Terzi, Barca, Cazzato, D'Amico, Lasorella, & Fracchiolla, 2021).

Numerous studies have investigated the energy and economic performance of horticultural production systems (Gökdoğan & Erdoğan, 2018; Mostashari-Rad, Nabavi-Pelesaraei, Soheilifard, Hosseini-Fashami, & Chau, 2019; Rajaeifar, Akram, Ghobadian, Rafiee, & Heidari, 2014). Olive orchards have also been the subject of such investigations. Özpinar (2020) evaluated the economic and energy implications of olive cultivation in Turkey across various slope gradients. Similarly, Hemmati, Tabatabaeefar, and Rajabipour (2013) present a detailed study of Iranian olive orchards, exploring the economic and energy implications of different slope conditions. Stillitano *et al.* (2017) conducted an assessment of the economic and energy performance of olive production, taking into account the final yield of olive seeds and by-products. Existing research has predominantly explored broad agricultural methodologies or specific parameters such as topographic slope and yield maximization within olive cultivation (Hemmati *et al.*, 2013; Özpinar, 2020; Stillitano *et al.*, 2017). However, a comprehensive, comparative analysis of the energetic and economic implications associated with chemical, mechanical, and integrated weed management strategies in olive orchards remains conspicuously absent. This study aims to bridge this critical knowledge gap by conducting a detailed evaluation of three distinct weed control systems employed in olive orchards located in Tarom County, Zanjan Province, Iran. By integrating rigorous energy and economic assessments, this research endeavors to provide novel insights into the sustainability of diverse weed control approaches, thereby contributing to the advancement of more resource-efficient and ecologically sound practices in olive production. Consequently, the primary objective of this investigation was to assess the energetic and economic performance of three discrete weed management systems- chemical (System I), mechanical (System II), and integrated (System III) - within olive orchards in Tarom County, Zanjan Province, Iran.

Materials and Methods

Study site and data collection

The study was conducted in Tarom County, which is located in Zanjan Province, Iran (36°49′36″N 48°53′48″E), during the year 2021. The region is situated within the warm, semi-arid climatic region of Zanjan, which is classified as a Mediterranean zone. The region receives an annual average precipitation of approximately 450 millimeters, exhibiting substantial monthly variability. The months of July and August experience the highest temperatures, with maximum values reaching up to 45 °C. Conversely, the coldest period occurs between December and February, with average temperatures of around -2.13 °C (IRIMO, 2024).

The determination of the sample size was achieved by implementing Cochran's sample size formula (Namdari *et al.*, 2024):

$$n = \frac{N(s \times t)^2}{(N-1)d^2 + (s \times t)^2} \quad (1)$$

where, n represents the sample size, and N represents the population size. The symbol s denotes the sample standard deviation. The term t signifies the critical t-value corresponding to a 95% confidence level, conventionally approximated as 1.96 for large sample sizes. Finally, d represents the permissible margin of error, established at 5% in this instance.

The sample size, calculated using Cochran's formula to ensure sufficient statistical power and adherence to established statistical standards, consisted of 50 participants. Data were collected through in-depth, face-to-face interviews with a randomly selected cohort of olive farmers from the designated study region.

The selected sample size was determined to ensure both statistical validity and representativeness of the broader olive-growing population in the study area. In addition to statistical considerations, factors such as variations in orchard management practices, geographical distribution, and farm sizes were taken into account (Mairech *et al.*, 2020; Soriano, Álvarez, Landa, & Gómez, 2014). This approach enhances the generalizability of the findings and ensures that the results accurately reflect the diversity of weed management systems used in olive orchards of the region (Terzi *et al.*, 2021).

Agricultural operations in the olive orchards of the study area typically commence in the spring season. Irrigation, which begins in April or May, relies on well water extracted using electric pumps. Fertilization and pest control measures are implemented throughout the spring and summer months, with commonly used herbicides including organophosphorus compounds, pyridine-based herbicides (selective against broadleaf weeds), glyphosate (a non-selective herbicide effective against both broadleaf weeds and grasses), and dinitroaniline-based pre-emergence herbicides that inhibit weed germination. Weed control methods vary depending on the system: chemical control relies on herbicide applications, mechanical control involves the use of hand mowers or tractor-mounted mowers, and integrated weed management combines reduced herbicide use with mechanical methods. The tractors used for agricultural operations are primarily MF285 or UTB-650 models, which are widely used and readily available in Iran. The primary fertilizers applied in olive cultivation consist of urea (46% N), triple superphosphate, zinc sulfate, potassium sulfate, farmyard manure, and dried poultry manure, supplemented by minor amounts of NPK fertilizers. Diesel fuel is essential for powering agricultural machinery and transporting inputs. The olive harvest, a labor-intensive process, begins in October, with all pre-harvest activities heavily reliant on human labor.

The dataset contained both descriptive and quantitative data related to the costs and inputs involved in various agricultural production processes. It included details about farm size, cultivated area, number of land parcels, land tenure arrangements, irrigation practices, and the use of machinery (such as types of tractors, equipment, and operational timings). In addition, the dataset provided information on energy sources, distinguishing between fossil fuels and electricity, as well as fuel consumption per operation. It also offered data on input application rates per hectare and yield-related factors, including labor needs, types and quantities of herbicides and fertilizers, manufacturers, and yield outcomes. Moreover, the dataset encompassed a thorough analysis of the entire production cycle, from planting to harvesting, covering harvesting techniques and transportation procedures (including operational processes, duration, and labor contributions). Additional data was obtained through interviews with agricultural managers from provincial offices and through consultation with records maintained by the Iranian Ministry of Agriculture.

Defining the comparative scenarios

Three distinct weed control approaches were adopted for the study area: a purely chemical approach (System I), a solely mechanical approach (System II), and an integrated approach combining both chemical and mechanical methods (System III). Common herbicides employed for weed and pest control include organophosphorus compounds, pyridine-based herbicides with selective toxicity towards broadleaf weeds, glyphosate, which is a widely used herbicide effective against both broadleaf weeds and grasses, and dinitroaniline-based pre-emergence herbicides that inhibit weed germination.

In practice, farmers adopt different weed management systems depending on various factors such as orchard type and size, irrigation system, mechanization level, and land slope. To accurately classify the weed control systems used in the studied orchards, in-depth interviews were conducted with farmers to determine the specific method employed in each orchard. This ensured a precise distinction between the different weed management systems. Additionally, periodic field inspections were carried out throughout the growing season to monitor the implementation of each system and verify that they were consistently applied under comparable conditions. Moreover, efforts were made to ensure that all systems were applied under similar environmental and management conditions, minimizing external variability that could affect the results. These measures helped maintain the reliability of the data and the validity of the comparative analysis.

Fossil fuel, electricity, and lubricant

Diesel fuel and electricity consumption for tractors, as well as water withdrawal, were calculated based on data collected from farmers. Diesel fuel consumption was estimated using tractor operational hours and average fuel consumption rates. Electricity consumption was calculated based on the power rating of electric pumps and their operational duration. Water withdrawal was estimated using the flow rate of irrigation pumps and total irrigation time. All data was cross-checked with official agricultural records and standard references to ensure accuracy. In terms of transportation, all materials and products involved in the olive production system were hauled by different transport facilities over various distances. Data for transportation were collected through interviews and direct measurements.

Conceptual framework for analysis of the energy and economic

For the energy analysis, physical inputs were converted to energy using energy conversion coefficients (Table 1). Values of energy are considered from the total agricultural production inputs, energy equivalents of input, and output.

The energy coefficients used in this study were adopted from widely recognized sources in the scientific literature. These coefficients are commonly utilized in energy analysis studies of agricultural systems to ensure consistency and comparability of results. While it is ideal to determine these coefficients based on the specific conditions of each region or country, previous research has shown that these values do not vary significantly across different geographical locations. Therefore, to maintain consistency with existing studies and ensure comparability, standard values from relevant literature have been used as references. The selected coefficients are well-established and widely accepted in energy analysis studies, ensuring the reliability and accuracy of the calculations (Hemmati *et al.*, 2013; Özpinar, 2020; Rahmani *et al.*, 2022).

Table 1- Energy equivalents of olive production in Tarom region, Iran

	Input/output		Unit	Energy use (MJ Unit^{-1})	Reference
			A. Input		
1	Human labor		h	1.69	(Hemmati *et al.*, 2013)
2	Machinery		h	62.7	(Hemmati *et al.*, 2013)
3	Diesel fuel		L	47.8	(Sharifi, Hafezi, & Aghkhani 2025)
4	Gasoline fuel		L	46.3	(Sharifi *et al.*, 2025)
		Nitrogen	kg	78.1	(Hemmati *et al.*, 2013)
		Phosphate	kg	17.4	(Hemmati *et al.*, 2013)
5	Fertilizer	Potassium	kg	13.7	(Hemmati *et al.*, 2013)
		Micronutrients	kg	120	(Hemmati *et al.*, 2013)
		Sulfur	kg	1.12	(Rajaeifar *et al.*, 2014)
		Herbicide	kg	85	(Khoshnevisan, Shariati, Rafiee, & Mousazadeh, 2014)
6	Pesticide	Pesticide	kg	115	(Khoshnevisan *et al.*, 2014)
		Fungicide	kg	295	(Khoshnevisan *et al.*, 2014)
7	Manure		kg	0.3	(Khoshnevisan *et al.*, 2014)
8	Electricity		kWh	12	(Hemmati *et al.*, 2013)
9	Water irrigation		m^3	1.02	(Hemmati *et al.*, 2013)
			B. Output		
1	Olive yield		kg	11.8	(Hemmati *et al.*, 2013)

In agricultural systems, energy demand can be categorized into four main types: direct energy (DE), indirect energy (IDE), renewable energy (RE), and non-renewable energy (NRE). Direct energy (DE) refers to the energy utilized directly on farms and fields, which includes human labor, irrigation water, diesel fuel, and electricity. Indirect energy (IDE) represents the energy embedded in the production, packaging, and transportation of agricultural inputs, such as chemical fertilizers, farmyard manure, biocides (pesticides), and machinery used in olive production. Renewable energy (RE) comprises energy derived from sustainable and naturally replenishable sources, including human labor, water for irrigation, and farmyard manure. In contrast, non-renewable energy (NRE) consists of energy derived from finite resources, such as machinery, diesel fuel, chemical fertilizers, biocides, and electricity (Hossein, Azizpanah, Namdari, & Shirkhani, 2024; Ghasemi Mobtaker, Akram, & Keyhani, 2012). This classification framework was applied to analyze the energy inputs associated with olive production under different weed control systems (I, II, and III).

In the context of energy systems analysis, a suite of key performance indices is routinely employed. These indices, which are frequently referenced in pertinent scholarly literature (Canakci, Topakci, Akinci, & Ozmerzi, 2005), encompass metrics such as energy efficiency, energy productivity, energy intensity, and net energy. The mathematical formulations for these indices are detailed in Equations 2 through 6 (Hossein *et al.*, 2024):

$$\text{Energy ratio} = \frac{\text{Output energy}}{\text{Input energy}} \quad (2)$$

$$\text{Energy productivity} = \frac{\text{Production}}{\text{Input energy}} \quad (3)$$

$$\text{Energy intensity} = \frac{\text{Input energy}}{\text{Production}} \quad (4)$$

$$\text{Net energy} = \text{Output energy} - \text{Input energy} \quad (5)$$

$$\text{Net energy ratio} = \frac{\text{Output energy} - \text{Input energy}}{\text{Input energy}} \quad (6)$$

For the economic analysis of olive production, the costs of inputs used in olive production were specified in order to calculate the benefit to cost ratio (BCR) by dividing total production revenue by the total production costs for one hectare of olive production. The total costs included variable costs and fixed costs; the variable costs were costs for human labor, machinery rent, repair, maintenance and service of machinery, chemical compounds, water for irrigation, farmyard manure, and chemicals; while summation of machinery depreciation, land rent, and interest gave the fixed cost.

To account for the financial costs associated with variable expenses, current capital interest was calculated. The interest rate was applied to half of the variable costs, reflecting the practical reality that farmers often finance only a portion of their variable costs through loans or credit. The interest rate used was 20%, based on the average annual interest rate reported by the Central Bank of Iran (CBI, 2024). This approach is consistent with methodologies used in previous studies (Artukoğlu, Olgun, & Adanacıoğlu, 2012).

Standardization of currency units to the United States Dollar (USD) was implemented to facilitate international comparability and adhere to prevalent practices within agricultural economic studies. All financial data were converted using the annual average market exchange rate for 2022, thus establishing a uniform basis for economic evaluation.

Economics analyses were measured using Eqs. 7-11 (Moosavi-Nezhad, Salehi, Aliniaeifard, Winans, & Nabavi-Pelesaraei, 2022).

$$\text{Total income} = \text{Yield} \times \text{Price} \tag{7}$$

$$\text{Gross profit} = \text{Total income} - \text{Variable cost of production} \tag{8}$$

$$\text{Net profit} = \text{Total income} - \text{Total production cost} \tag{9}$$

$$\text{Benefit} - \text{cost ratio} = \frac{\text{Total income}}{\text{Production cost}} \tag{10}$$

$$\text{Productivity} = \frac{\text{Olive yield}}{\text{Production cost}} \tag{11}$$

The equations used in this study for calculating energy and economic indices are well-established and widely applied in previous research on agricultural production systems. These equations have been extensively utilized in the literature to ensure consistency and comparability across different studies (Banaeian, Zangeneh, & Clark, 2020; Zangeneh, Banaeian, & Clark, 2021). By employing these standard formulas, this study aligns with existing methodologies, allowing for direct comparison of results with those of other studies.

Results and Discussion

In the present study, the energy consumption and economic assessment indexes of olive production were conducted for three weed control methods.

Energy analysis of olive production in different systems

Table 2 shows the results of assessing the energy balance of olive production. The energy level and amount of consumption of inputs have been measured in three weed control systems. Total annual energy inputs were 64,297.16 MJ ha^{-1}, and 76,886.83 MJ ha^{-1} for Systems I and II, respectively. In contrast, about 93,069.16 MJ ha^{-1} energy input was calculated for System III (Table 2). Energy is used in every stage of the crop production process, from land preparation to harvesting. Therefore, identifying sustainable methods for weed control in olive orchards is crucial for sustainable agriculture. Based on previous studies, the range of total energy consumption was 7,380.5-31,098.2 MJ ha^{-1} for olive in Turkey (Özpinar, 2020), 118,125 MJ ha^{-1} in olive production in Greece (Genitsariotis, Chlioumis, Tsarouhas, Tsatsarelis, & Sfakiotakis, 1998), about 15.9–23.3 GJ ha^{-1} in flat land and sloping land olive orchards in IRI (Hemmati et al., 2013). The energy consumption of olive inputs in System III was 30.91% and 17.39% higher than the energy consumption of Systems I and II, respectively (Table 2). On the other hand, the total energy input of System I and System II were approximately 30.91% and 17.39%, respectively, less than that of System III practiced by farmers (Table 2). Our findings showed that chemical weed control (System I) causes lower energy consumed per hectare for olive production compared to other systems. The low energy consumption in System I can be seen as the reason for saving electricity, gasoline fuel, and machinery compared to the other two systems (Table 2). In recent decades, energy was intensified as an extensive debate on sustainable development, especially in the agricultural sector. In many countries, the limitation of energy and its high price have caused it to be recognized as a limiting factor, and for this reason, various solutions have been proposed to reduce energy input in agricultural production. This is happening because, among several energy supply solutions to meet our society's current requirement, for producers, decreasing input energy has been one of the elected solutions.

The electricity, fertilizers, energy, and water irrigation, respectively, have the biggest share of total energy input in all systems (Figure 1). Olive orchards have an intensive demand for electricity. The result illustrated that electricity accounts for the majority of energy consumption, representing 62.82%, 65.53%, and 57.43% of the total energy input in olive production Systems I, II, and III, respectively (Figure 1). After electricity, the main energy-consuming inputs respectively were fertilizers, water irrigation, labor, gasoline fuel, and pesticides (Table 2). Consistent findings have been reported in previous studies, aligning with the results of the present study (Basavalingaiah et al., 2020; Cellura, Longo, & Mistretta, 2011; Nikkhah et al., 2015; Ozkan et al., 2004a; Rigamonti et al., 2009; Zhang et al., 2011). The observed variability in input energy across the different weed control systems can be attributed to differential utilization of electricity, chemical fertilizers, biocides, and labor (Babushkina, Belokopytova, Grachev, Meko, & Vaganov, 2017).

The variation in chemical fertilizer consumption across different weed management systems can be attributed to several factors. In the chemical control system, herbicides effectively reduce weed competition, allowing olive trees to utilize soil nutrients more efficiently, thereby reducing the need for additional fertilization (Radjabov, Troyanovskaya, Dvoryashina, Vanzha, & Akhtyamova, 2025; Shrestha, Timsina, Subedi, Pokhrel, & Chaudhary, 2019). In contrast, the mechanical control system involves mowing, which, while suppressing weeds, may disturb the soil and accelerate organic matter decomposition, leading to a moderate increase in fertilizer demand (Formaglio, Veldkamp, Duan, Tjoa, & Corre, 2020; Mohanty, Nanda, Mishra, & Padhiary, 2020). The integrated system combines mechanical and chemical weed control methods, which can intensify soil disturbance and impact microbial activity, potentially reducing soil fertility. As a result, farmers may apply more fertilizers in this system to compensate for nutrient loss and maintain optimal tree growth (Abdul Rahman, Larbi, Opoku, Tetteh, & Hoeschle-Zeledon, 2019; Mohanty *et al.*, 2020; Saini *et al.*, 2023).

The annual energy output from olive production for each system was as follows: System I produced 47,648.4 MJ ha^{-1}, System II yielded 36,709.8 MJ ha^{-1}, and System III generated 38,161.2 MJ ha^{-1} (Table 2). The most common and important aim for all agricultural producers is to increase the final production. The increase in the final product and by-product has a direct relationship with the output energy. The highest output energy was observed in System I (Table 2). In other words, it also yielded the greatest quantity of olive seeds.

Table 2- Energy inputs and output of olive production in Tarom region, Iran

	Item	Unit	Olive					
			System I		System II		System III	
			Value (per unit)	Energy (MJ ha^{-1})	Value (per unit)	Energy (MJ ha^{-1})	Value (per unit)	Energy (MJ ha^{-1})
		A. Input						
	Human labor	h	718.96	1215.04	594.1	1004.03	539.97	912.55
	Machinery	h	5.59	350.49	42.92	2691.08	70.96	4449.19
	Diesel fuel	L	4.44	212.23	0.39	18.64	16.46	786.79
	Gasoline fuel	L	29.02	1343.63	39.61	1833.94	64.08	2966.90
Fertilizer	Nitrogen	kg	129.5	10113.95	137.5	10738.75	171	13355.10
	Phosphate	kg	51.5	896.1	77.5	1348.5	129.5	2253.3

	Potassium	kg	38.5	527.45	79.5	1089.15	134	1835.8
	Micronutrients	kg	0.27	32.4	4	480	35.13	4215.6
	Sulfur	kg	0	0	3	3.36	34.25	38.36
Pesticide	Herbicide	kg	2	170	1.44	122.4	2.06	175.1
	Pesticide	kg	12.91	1484.65	0	0	8.14	936.1
	Fungicides	kg	0.15	44.25	0.62	182.9	0.48	141.6
	Manure	kg	2130	639	3210	963	6630	1989
	Electricity	kWh	3365.71	40388.52	4198.75	50385	4454.33	53451.96
	Water irrigation	m^3	6744.56	6879.45	5907.92	6026.08	5452.75	5561.81
	Total inputs	MJ	-	64297.16	-	76886.83	-	93069.16
	B. Output							
	Olive yield	kg	4038	47648.4	3111	36709.8	3234	38161.2

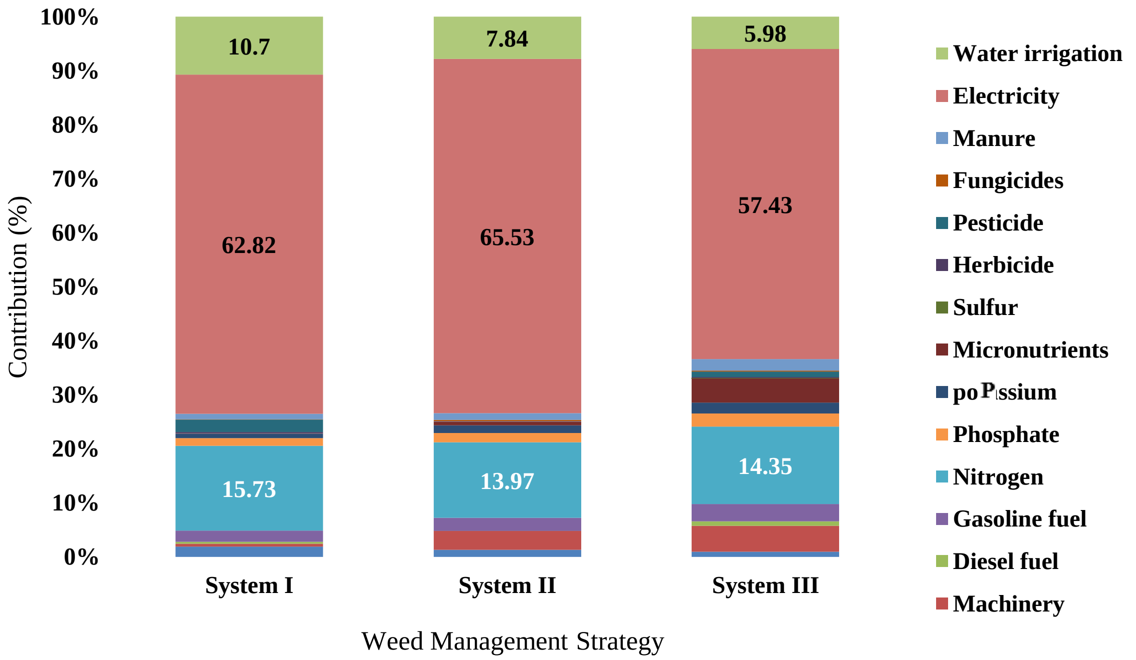


Fig. 1. Energy inputs in different weed control systems (chemical, mechanical, and integrated) for olive production

The product yield, energy input and output, energy ratio, energy productivity, energy intensity, net energy received, and net energy ratio of olive production in the Tarom region are presented in Table 3. The average olive production for Systems I, II, and III has been calculated to be 4,038 kg ha^{-1}, 3,111 kg ha^{-1}, and 3,234 kg ha^{-1}, respectively (Table 3). A comparative analysis of the energy ratios for Systems I, II, and III, as presented in Table 3, reveals that System I has an energy ratio of 0.74, while Systems II and III exhibit significantly lower ratios of 0.48 and 0.41, respectively. A review of the literature indicates a wide variability in energy ratios for olive production. For instance, Guzmán and Alonso (2008) reported energy ratios ranging from 0.5 to 3.8 for Spanish olive production, with variations attributed to factors such as irrigation systems and geographical location. Differences in energy ratios are influenced by production systems, geographical conditions, irrigation methods, farm management practices, and crop yields.

Furthermore, a comparison of energy productivity values in Table 3 shows that the chemical weed control system (System I) achieved a higher energy productivity (0.06 kg MJ^{-1}) compared to the mechanical and integrated systems (0.04 kg MJ^{-1} and 0.03 kg MJ^{-1} for Systems II and III, respectively). The highest energy intensity was observed in System III (28.78 MJ kg^{-1}), followed by Systems II (24.71 MJ kg^{-1}) and I (15.92 MJ kg^{-1}).

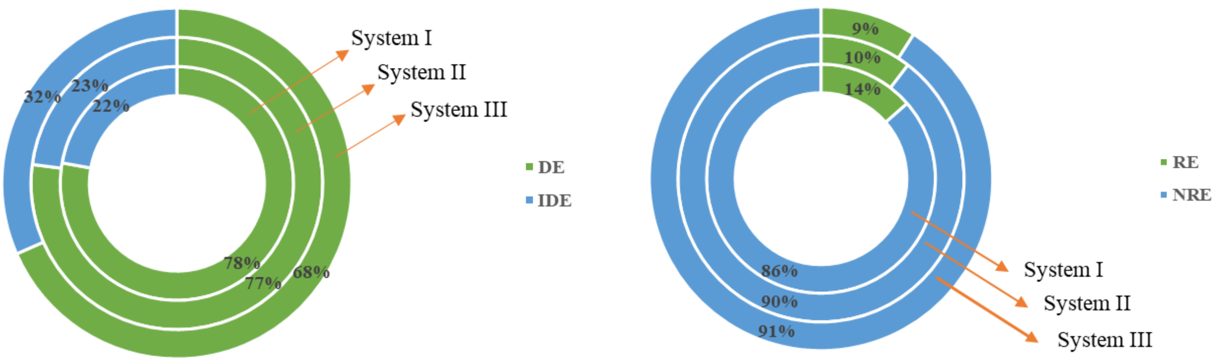
However, the net energy values for Systems I, II, and III were calculated as -16,648.8 MJ ha^{-1}, -40,177 MJ ha^{-1}, and -54,908 MJ ha^{-1}, respectively (Table 3). The consistently negative net energy values and net energy ratios across all examined systems reveal that energy is not conserved in the olive production processes, regardless of the system analyzed. Similar negative net energy values have been reported in the production of other fruit crops, such as apples (Naderi, Raini, & Taki, 2020) and oranges (Mohammadshirazi, Akram, Rafiee, & Kalhor, 2014), highlighting the energy-intensive nature of fruit production systems.

Table 3- Energy indices of olive production

	Item	Unit	Olive		
			System I	**System II**	**System III**
			Average		
1	Olive yield	kg ha^{-1}	4038	3111	3234
2	Energy input	MJ ha^{-1}	64297.16	76886.83	93069.16
3	Energy output	MJ ha^{-1}	47648.4	36709.8	38161.2
4	Energy ratio	-	0.74	0.48	0.41
5	Energy productivity	kg MJ^{-1}	0.06	0.04	0.03
6	Energy intensity	MJ kg^{-1}	15.92	24.71	28.78
7	Net energy	MJ ha^{-1}	-16648.8	-40177	-54908
8	Net energy ratio	-	-0.26	-0.52	-0.59

In this study, various forms of energy, including direct, indirect, renewable, and non-renewable energy, were calculated for the investigated systems. The contribution of each energy form to the total energy input is presented in Figure 2. System I demonstrated the lowest direct energy input (50,038.87 MJ ha^{-1}), primarily attributed to reduced reliance on human labor, diesel fuel, and electricity compared to mechanical (System II: 59,267.69 MJ ha^{-1}) and integrated (System III: 63,680.01 MJ ha^{-1}) systems. This efficiency stems from the minimized labor and machinery operations inherent to chemical interventions. Furthermore, System I exhibited the lowest indirect energy consumption (14,258.29 MJ ha^{-1}), owing to limited dependence on chemical fertilizers and agricultural machinery. In contrast, System III, which combines chemical and mechanical methods, recorded the highest IDE (29,389.15 MJ ha^{-1}), reflecting the cumulative energy demands of both approaches.

A critical distinction emerged in renewable energy (RE) and non-renewable energy (NRE) contributions. System I achieved the highest proportion of RE (8,733.49 MJ ha^{-1}), derived predominantly from human labor, irrigation water, and manure, indicating its superior energy efficiency. Conversely, System III relied heavily on NRE (84,605.8 MJ ha^{-1}), driven by extensive use of diesel fuel, chemical fertilizers, pesticides, and machinery. System II, while intermediate in NRE consumption (68,893.72 MJ ha^{-1}), still lagged behind System I in overall energy efficiency. These findings highlight the energy-related advantages of System I: its lower NRE and higher RE shares position it as the most energy-efficient option, whereas Systems II and III's greater dependence on non-renewable resources results in higher energy consumption.



a) Direct energy vs indirect energy b) Renewable energy vs non-renewable energy

Fig. 2. Classification of energy forms (direct, indirect, renewable, and non-renewable) in different weed control systems (chemical, mechanical, and integrated)

The energy indices provide a deeper understanding of key problems and discover important relationships that are not evident with basic statistics. These are useful tools for policymakers and the public to communicate energy issues related to sustainable development and promote institutional dialogue (Razmjoo, Sumper, & Davarpanah, 2019; Vera & Langlois, 2007). The results of the energy analysis demonstrate that System I (chemical weed control) is the most energy-efficient approach for weed management in olive orchards. System I outperformed the other systems, achieving the highest energy ratio, maximum net energy, greatest share of renewable energy, and peak energy productivity, making it the most reliable method for weed control in olive orchards.

Economic analysis of olive production of different systems

Some economic indices including total costs, variable and fixed costs of production, and total production revenue were estimated to assess the economic profile of olive production (Table 4). The total variable cost of production was calculated for Systems I (1,326.54 \$ ha^{-1}), II (1,200.56 \$ ha^{-1}), and III (1,547.85 \$ ha^{-1}). Also, the fixed cost of production was found to be 1,481.48 \$ ha^{-1} for all three systems (Table 4). System III incurred the highest total production cost at \$3,029.33 per hectare, followed closely by System I at \$2,802.02 per hectare. System II recorded the lowest total production cost at \$2,682.04 per hectare (Table 4).

Table 4- Economic analysis of olive production

Item	System I		System II		System III	
	Costs ($ ha^{-1})	% (%)	Costs ($ ha^{-1})	% (%)	Costs ($ ha^{-1})	% (%)
A. Variable costs						
Chemical fertilizers	38.18	2.88	63.4	5.28	103.58	6.69
Micronutrients	1.74	0.13	8.81	0.73	103.21	6.67
Manure	31.27	2.36	42.8	3.56	88.4	5.71
Chemical compounds	86.56	6.53	18.63	1.55	64.70	4.18
Diesel fuel	0.05	0	0	0	0.22	0.01
Gasoline fuel	1.07	0.08	1.48	0.12	2.37	0.15
Engine oil	0	0	1.37	0.11	1.16	0.08
Electricity	45.75	3.45	57.07	4.75	60.55	3.91
Seasonal worker	822.67	62.02	687.56	57.27	752.50	48.62
Irrigation water	118.6	8.94	177.36	14.77	130.86	8.45
Operating or renting agricultural machines	60.05	4.53	32.94	2.74	99.58	6.43
Current capital interest (variable cost/2* %20)	120.59	9.09	109.14	9.09	140.71	9.09
Total variable costs	1326.54	-	1200.56	-	1547.85	-
B. Fixed costs						

Land rent	1481.48	100	1481.48	100	1481.48	100
Total fixed costs	1481.48	-	1481.48	-	1481.48	-
C. Total production costs	2808.02	-	2682.04	-	3029.33	-

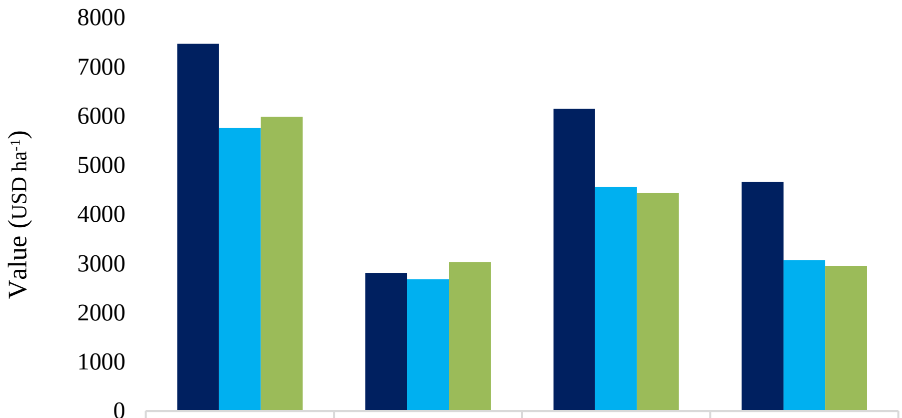
Table 4 demonstrates that labor constituted the predominant variable cost across all systems. Specifically, labor expenses accounted for approximately 62% of the variable costs in System I, 57% in System II, and 49% in System III. Following labor, costs associated with capital interest, irrigation water, chemical fertilizers, and agricultural machinery represented the subsequent significant variable expenditures. Labor costs, particularly those incurred during harvesting and pruning, have been repeatedly identified as the principal determinant of variable costs in olive production systems, as evidenced by research from Pergola *et al.* (2013), Artukoğlu *et al.* (2012), and Özpinar (2020). The present study's results validate these prior findings. A comprehensive breakdown of the costs and incomes for each system is presented in Table 4.

A comprehensive analysis of economic performance was undertaken, encompassing the estimation of key indices such as revenue, total production costs, gross profit, net profit, benefit-cost ratio, and productivity (Figures 3 and 4). In comparison to Systems II and III, System I demonstrated a significantly higher average olive income, boasting increases of 29.7% and 25.1%, respectively. Revenue was 7,470.3 $ ha^{-1}, 5,755.35 $ ha^{-1}, and 5,289.2 $ ha^{-1} in systems I, II, and III, respectively (Figure 3).

System I exhibited a superior gross profit (6,143.75 $ ha^{-1}) compared to Systems II (4,554.79 $ ha^{-1}) and III (4,435.05 $ ha^{-1}), indicating enhanced profitability. This trend was further substantiated by the net profit results, which were 4,662.28, 3,073.31, and 2,953.57 $ ha^{-1} for Systems I, II, and III, respectively.

A comparative analysis revealed that System I demonstrated the highest benefit-cost ratio (2.66) and productivity index (1.44 kg $$^{-1}$) among the three systems evaluated. Systems II and III exhibited lower values, with benefit-cost ratios of 2.16 and 1.97, and productivity indices of 1.16 kg $$^{-1}$ and 1.07 kg $$^{-1}$, respectively. Rahmani et al. (2022) reported benefit-cost ratios of 3.72 and 1.84 for semi-mechanized and traditional olive production systems, respectively. These findings provide a comparative benchmark and are consistent with the benefit-cost ratios observed in the present study, further validating the economic viability of the studied systems.

The common goal of many producers is to maximize profits while minimizing production costs. Energy optimization of plant production is an essential aspect of the general goal of improving energy efficiency worldwide. A critical strategy for achieving this objective lies in the judicious application of appropriate techniques throughout the plant's life cycle. A large portion of these processes is the choice of suitable solutions for weed control with minimal energy consumption. System I showed a lower amount of input energy and a higher output than the other two systems. However, it is possible to reduce the cost of olive production by using appropriate optimization methods (Angnes, de Almeida, Milan, & Romanelli, 2021; Htwe *et al.*, 2021; Kumar, Tirkey, & Shukla, 2021; Yousefi *et al.*, 2014).



	Total Income	Total Cost	Gross Profit	Net Profit
System I	7470.3	2808.02	6143.76	4662.28
System II	5755.35	2682.04	4554.79	3073.31
System III	5982.9	3029.33	4435.05	2953.57

Fig. 3. Comparison of economic indicators (total income, total cost, gross profit, and net profit) for weed control systems (chemical, mechanical, and integrated)

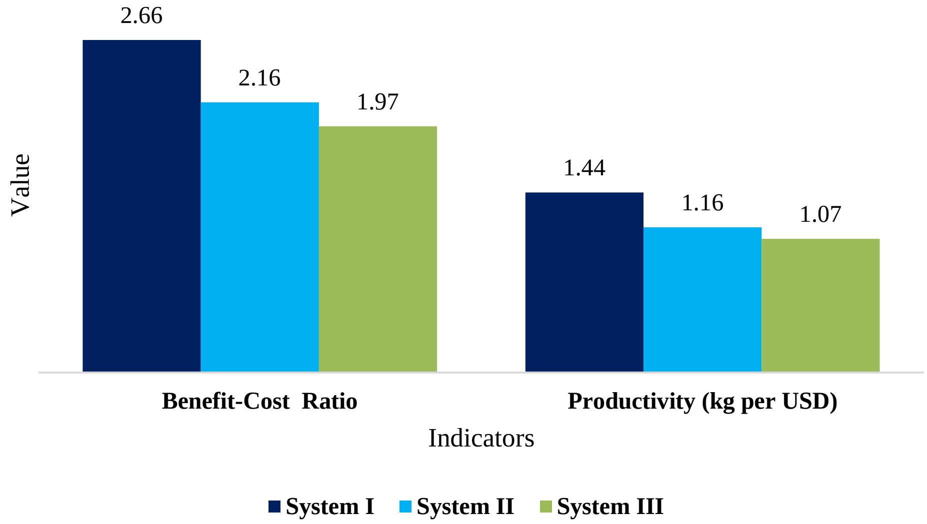


Fig. 4. Comparison of benefit-cost ratio and productivity for weed control systems (chemical, mechanical, and integrated)

While System I demonstrated the highest energy efficiency and cost-effectiveness, it relies on chemical weed control, which may pose environmental risks such as soil and water contamination, potential harm to non-target organisms, and herbicide resistance development. These factors highlight the need for cautious and optimized application of chemical methods to minimize negative environmental impacts (Beckie, Ashworth, & Flower, 2019; Fishkis & Koch, 2022; Perveen *et al.*, 2019).

On the other hand, System III, which integrates chemical and mechanical weed control, offers a balanced approach by reducing total herbicide use while maintaining weed suppression. Further optimization of this integrated approach, such as precision herbicide application, improved mechanical techniques, or complementary biological control methods, could enhance its sustainability by reducing chemical dependency while maintaining cost-effectiveness and energy efficiency (Loddo, McElroy, & Giannini, 2021; Riemens, Sønderskov, Moonen, Storkey, & Kudsk, 2022).

The findings of this study have broader implications for policy and practice in the olive production sector. The superior performance of the chemical control system (System I) in terms of energy efficiency and cost-effectiveness suggests that, with appropriate environmental safeguards, this approach could be scaled up in regions aiming to optimize resource use. However, the potential environmental risks associated with extensive chemical use underscore the need for regulations and best management practices to mitigate adverse impacts. Additionally, the integrated system (System III), while slightly less efficient, presents opportunities for further optimization to balance economic performance with environmental protection.

Although the findings of this study are specific to olive orchards in Tarom County, Zanjan Province, the methods and results may be applicable to other regions with similar climatic, agricultural, and economic conditions. However, local variations, such as soil types, crop varieties, and farming practices, could influence the generalizability of these results. Additionally, while this study provides valuable insights into the energy consumption and economic performance of different weed management systems, it primarily focuses on these two aspects and does not address the environmental and social dimensions, such as biodiversity, soil health, and labor conditions, which are also essential for assessing the overall sustainability of agricultural practices. These factors, however, were beyond the scope of this study. Future research should incorporate these dimensions to offer a more comprehensive evaluation of the sustainability of olive cultivation systems, considering not only energy and economic performance but also environmental and social impacts.

Conclusion

This study demonstrates that the choice of weed control method significantly affects both energy consumption and economic performance in olive production systems. Among the three evaluated systems, the chemical weed control method (System I) required 47,648.4 MJ ha^{-1} of energy input and achieved an energy use efficiency of 0.74. The total production cost in this system was 2,808.02 \$ ha^{-1}, generating a net profit of 4,662.28 \$ ha^{-1}.

However, while System I is the most energy-efficient and economically viable option, it poses potential environmental risks, such as soil and water contamination, herbicide resistance, and harm to non-target species. Therefore, relying solely on chemical methods might not align with broader sustainability goals in the long term.

In contrast, the mechanical weed control method (System II) required 36,709.8 MJ ha^{-1} of energy input and had an energy use efficiency of 0.48, with a total production cost of 2,682.04 \$ ha^{-1}, and a net profit of 3,073.31 \$ ha^{-1}. The integrated weed control system (System III) combined chemical and mechanical methods, resulting in an energy input of 38,161.2 MJ ha^{-1}, an energy efficiency of 0.41, a production cost of 3,029.33 \$ ha^{-1}, and a net profit of 2,953.57 \$ ha^{-1}. While System III reduced chemical input, it required higher machinery investment and labor, increasing costs in the short term.

System III, with its integrated approach, offers a promising compromise by reducing chemical input and integrating mechanical methods, which can mitigate some of the environmental risks. However, it may require higher initial investments in machinery and more labor, potentially increasing costs in the short term. Moreover, its environmental impact could still be substantial due to mechanical operations that disturb soil and increase water loss.

These findings underscore the critical importance of selecting sustainable and energy-efficient practices within agricultural production systems. The results highlight the potential of System I in enhancing energy efficiency and economic sustainability within the olive cultivation sector. However, they also stress the importance of adopting a strategy that carefully reconciles energy efficiency, economic viability, and environmental conservation. Future research should focus on optimizing integrated weed management approaches that minimize reliance on chemical herbicides while maintaining energy efficiency and economic viability. Exploring alternative strategies such as biological weed control, cover cropping, and precision agriculture technologies can help reduce chemical inputs and mitigate environmental risks. Additionally, assessing the long-term trade-offs between different weed control systems, including their impacts on soil health, water resources, and biodiversity, is essential. By refining sustainable weed management techniques, future studies can contribute to a more resilient and eco-friendly agricultural system.

Authors Contribution

B. Mohammadi: Formal analysis, Data curation

A. R. Yousefi: Conceptualization, Methodology, Writing original draft preparation, writing-review and editing

M. Namdari: Conceptualization, Methodology, Formal analysis, Investigation and resources, Data curation, Writing original draft preparation, Writing-review and editing

M. Heydari: Methodology, Data curation, Writing original draft preparation, Writing-review and editing

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ارزیابی انرژی و اقتصادی سیستم‌های تولید زیتون: مقایسه‌ای از استراتژی‌های مدیریت علف‌های هرز شیمیایی، مکانیکی و تلفیقی

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چکیده

این مطالعه مصرف انرژی و عملکرد اقتصادی سه روش کنترل علف‌های هرز در باغ‌های زیتون شهرستان طارم، استان زنجان را با تمرکز بر کشاورزی پایدار ارزیابی می‌کند. هدف، ارزیابی بهره‌وری انرژی و مقرون‌به‌صرفه‌بودن سیستم‌های مختلف مدیریت علف‌های هرز است. این تحلیل شامل کنترل شیمیایی علف‌های هرز (سیستم I)، کنترل مکانیکی (سیستم II) و روش تلفیقی علف‌های هرز (سیستم III) است. داده‌ها از طریق مصاحبه با ۵۰ باغدار زیتون جمع‌آوری شد. نتایج نشان می‌دهد که کل مصرف انرژی در سیستم III (۹۳۰۶۹/۱۶ مگاژول در هکتار) بالاترین و در سیستم I (۶۴۲۹۷/۱۶ مگاژول در هکتار) پایین‌ترین میزان را داشت. سیستم I همچنین بهره‌وری انرژی برتر (۰/۷۴)، انرژی خروجی (۴۷۶۴۸/۴۰ مگاژول در هکتار) و بهره‌وری انرژی (۰/۰۶ کیلوگرم در مگاژول) را نشان داد و آن را به قابل‌اجراترین گزینه برای بهینه‌سازی مصرف انرژی تبدیل کرد. از نظر اقتصادی، سیستم I بالاترین سود خالص (۴۶۶۲/۲۸ دلار در هکتار) و نسبت سود به هزینه (۲/۶۶) را ایجاد کرد و از سیستم‌های II (۳۰۷۳/۳۱ دلار در هکتار؛ نسبت سود به هزینه: ۲/۱۶) و III (۲۹۵۳/۵۷ دلار در هکتار؛ نسبت سود به هزینه: ۱/۹۷) عملکرد بهتری داشت. این مطالعه نتیجه می‌گیرد که سیستم I، با استفاده کارآمد از انرژی‌های تجدیدپذیر، از نظر عملکرد انرژی و اقتصادی، قابل‌اجراترین گزینه است و تعادلی بین ورودی انرژی کم و بازده بالا ایجاد می‌کند، بنابراین سود را به حداکثر و هزینه‌های تولید را به حداقل می‌رساند. این یافته‌ها بر اهمیت انتخاب روش‌های مناسب کنترل علف‌های هرز برای بهینه‌سازی مصرف انرژی و کاهش هزینه‌های کلی تولید در کشت زیتون تأکید می‌کنند.

واژه‌های کلیدی: انرژی، پایداری، علف‌های هرز، کارایی، مقرون‌به‌صرفه بودن

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