



A comparative assessment of energy input-output in wheat production across different tillage systems

Alireza Keikha¹, Mohammad Gholami Parashkoohi^{2*} , Ahmad Mohammadi²,
Hamed Afshari³

¹ Department of Biosystem Engineering, Tak.C., Islamic Azad University, Takestan, Iran

² Department of Mechanical Engineering, ShQ.C., Islamic Azad University, Shahr-e Qods, Iran

³ Department of Food Science and Engineering, CT.C., Islamic Azad University, Tehran, Iran

Article Info	Abstract
Article type: Research Article	Wheat (<i>Triticum</i> spp.) is a vital staple crop worldwide, essential for sustainable agriculture and food security. This study examines the energy inputs and outputs associated with wheat production, specifically comparing conventional and conservation tillage systems within the Sistan and Baluchistan Province. The analysis not only highlights energy consumption but also evaluates key metrics of energy efficiency. A comparison of the two tillage methods reveals significant differences in energy usage: conventional tillage demands a total energy input of 49,612.99 MJ ha ⁻¹ , while conservation tillage only requires 37,972.36 MJ ha ⁻¹ . This considerable reduction in energy input illustrates the greater energy efficiency of conservation tillage, which has an energy use efficiency ratio of 5.20, compared to 3.80 for conventional tillage. Additionally, the input-output analysis indicates that conservation tillage leads to lower labor requirements, decreased machinery usage, and reduced application of chemical fertilizers and biocides. To promote the sustainability of wheat production, it is advisable for farmers in Sistan and Baluchistan to adopt conservation tillage practices. This shift can enhance energy efficiency, lower production costs, and mitigate environmental impacts. Policymakers should focus on raising awareness and providing training on conservation tillage techniques to assist in this transition. Moreover, research institutions can contribute by conducting further investigations into the long-term advantages of conservation tillage and establishing support programs to encourage farmers to embrace more sustainable practices. Lastly, the integration of technology and innovative agricultural methods can further optimize energy consumption and enhance the overall sustainability of wheat farming.
Article history: Received: December 2024 Accepted: October 2025	
Corresponding author: gholamihassan@yahoo.com	
Keywords: Conservation tillage Energy efficiency Sustainable agriculture Tillage systems Wheat production	

Cite this article: Keikha, Alireza; Gholami Parashkoohi, Mohammad; Mohammadi, Ahmad; Afshari, Hamed. 2025. A comparative assessment of energy input-output in wheat production across different tillage systems. *Environmental Resources Research*, 13(2), 207-219.



Introduction

Wheat is a staple crop that plays a crucial role in global food security, providing essential nutrients and sustenance to billions of people. As the demand for wheat continues to rise due to population growth and changing dietary patterns, enhancing the efficiency of its production becomes imperative. One of the critical factors influencing wheat yield and sustainability is the tillage system employed in agricultural practices (Khan et al., 2010). Tillage affects not only soil health and structure but also the energy dynamics associated with crop production. In recent years, there has been increasing attention on the energy inputs and outputs of agricultural systems, particularly in wheat production (Pourmehdi and Kheiralipour, 2023). Energy input-output assessments provide valuable insights into the sustainability and efficiency of different agricultural practices by analyzing the energy invested in inputs (such as seeds, fertilizers, pesticides, and machinery) relative to the energy obtained from the harvested crop (Pourmehdi and Kheiralipour, 2024). Various tillage systems, including conventional tillage, reduced tillage, and no-till, exhibit distinct energy profiles due to differences in soil disturbance, nutrient management, and operational practices. Sustainable agriculture refers to farming practices that aim to meet the needs of the present without compromising the ability of future generations to meet their own needs. This approach emphasizes the importance of environmental health, economic profitability, and social equity. Sustainable agriculture promotes biodiversity, soil health, and water conservation, while reducing reliance on synthetic chemicals and fossil fuels (Soltani et al., 2013). It encourages the use of organic fertilizers, crop rotation, and integrated pest management to enhance ecosystem resilience. Additionally, community engagement and ethical labor practices are vital components of sustainable agriculture, ensuring that farming systems support local economies and promote fair treatment of workers (Ahmad et al., 2018). By adopting these practices, sustainable agriculture seeks to create a food system that is productive, equitable, and capable of adapting to the challenges posed by climate change and resource depletion. Through

education and innovation, it aims to transform traditional agricultural methods into ones that are more harmonious with the environment and society. Overall, sustainable agriculture represents a holistic approach that balances productivity with environmental stewardship and social responsibility. Tillage systems refer to the agricultural practices used for preparing soil for planting crops. There are several approaches to tillage, each with its own set of advantages and disadvantages. Conventional tillage involves the complete turning of the soil using plows or harrows. This method helps to incorporate crop residues and control weeds but can lead to soil erosion, loss of moisture, and disruption of soil structure (Ghasemi-Mobtaker et al., 2022). Conservation tillage reduces the frequency and intensity of soil disturbance. It includes practices such as no-till and reduced-till, where minimal disturbance is made to the soil surface. This system helps maintain soil structure, reduces erosion, conserves moisture, and can enhance soil health by promoting beneficial microbial activity. Ultimately, the choice of tillage system depends on various factors, including soil type, climate, crop rotation, and the specific goals of the farmer. Each system requires careful management to balance productivity with sustainability (Alhajj Ali et al., 2013).

The study conducted an energy input-output analysis of conventional tillage (CT), reduced tillage (RT), and zero tillage (ZT) methods during the second crop corn production. The trials took place from 2015 to 2016 at the Ceylanpinar Directorate of Agricultural Enterprises in the Karatas region of Turkey. The results indicated that ZT required the least energy input ($23,724.15 \text{ MJ ha}^{-1}$), while CT produced the highest energy output ($138,510 \text{ MJ ha}^{-1}$). In terms of energy productivity, ZT had the highest value at 5.54. CT yielded the most corn, with an output of $9,500 \text{ kg ha}^{-1}$, followed by ZT with $9,100 \text{ kg ha}^{-1}$ and RT with $8,750 \text{ kg ha}^{-1}$. Ultimately, although CT is favored for its higher yield, the findings suggest that ZT and RT methods should be promoted for their ecological benefits and superior energy productivity (Saglam et al., 2020). Identifying a tillage production system that minimizes energy use

and carbon emissions while maximizing crop productivity is crucial for environmental sustainability. This study conducted a comprehensive analysis over four years (2016–2019) across three major agroecosystems in eastern India: the eastern Indo-Gangetic plain, coastal regions, and hill & plateau areas. It evaluated six rice-based production systems with varying levels of mechanization: fully mechanized, partly mechanized, and traditional tillage. The findings revealed that chemical fertilizers were the largest energy input source, accounting for 44% of energy use in partly mechanized tillage and 38% in fully mechanized tillage. Diesel, irrigation, plant protection chemicals, seeds, and electricity followed. In traditional tillage, seeds, human labor, animal energy, and farmyard manure contributed 21%, 20%, 16%, and 16% of the total energy input, respectively. Mechanized tillage had the highest energy input (52,161 MJ ha⁻¹), while traditional tillage had the lowest (16,879 MJ ha⁻¹). The eastern Indo-Gangetic plain cropping systems were more energy-intensive (50,908 MJ ha⁻¹) compared to coastal systems (27,459 MJ ha⁻¹). Mechanized tillage produced significantly higher energy outputs (395,245 MJ ha⁻¹) compared to partly mechanized and traditional systems. Partly mechanized tillage and coastal agroecosystems were identified as the most energy-efficient, with energy ratios of 8.88 and 9.81, respectively. However, mechanized tillage was found to be more carbon-intensive than the other systems. It demonstrated higher carbon efficiency (3.75) and a carbon sustainability index (2.75), but had a lower carbon footprint per yield compared to traditional tillage. In terms of productivity, mechanized tillage outperformed partly mechanized and traditional systems by 22% and 73%, respectively. Additionally, partly mechanized tillage had a 23% lower cultivation cost than fully mechanized tillage. Overall, the study concluded that partly mechanized tillage is the most energy and carbon-efficient production system for eastern India (Kumar et al., 2021).

This study contributes to the existing literature by providing a comprehensive

comparative analysis of energy efficiency across various tillage practices, specifically focusing on their implications for sustainable agricultural practices. While previous research has often examined energy consumption in isolation for specific tillage methods, the work integrates a broader perspective by assessing not only the energy inputs but also the outputs in terms of yield and overall production efficiency. This holistic approach allows us to identify more sustainable tillage practices that optimize energy use while maintaining or enhancing crop productivity. Moreover, findings reveal critical insights into the relationship between tillage systems and energy efficiency that have not been thoroughly explored in earlier studies. By quantifying these relationships, we can offer concrete recommendations for farmers and policymakers aimed at reducing energy expenditure in wheat production, which has significant implications for agricultural sustainability. Regarding the applicability of our results to other scientific disciplines, our methodology and findings may resonate with researchers in environmental science, agronomy, and economics. The quantitative framework we used to analyze energy input-output can be adapted to assess other crop production systems and agricultural practices, potentially influencing a wide range of disciplines concerned with resource management, sustainability, and efficiency.

This comparative assessment aims to evaluate the energy input-output ratios of wheat production across various tillage systems, highlighting the implications for agricultural sustainability and food security. By examining the energy efficiency of each system, this study seeks to inform farmers, agronomists, and policymakers about the potential benefits and trade-offs associated with different tillage practices. Ultimately, understanding these dynamics will contribute to the development of more sustainable agricultural systems that maximize productivity while minimizing energy consumption and environmental impact.

Materials and methods

Location of the study area

Sistan and Baluchistan Province is categorized within the desert and dry climate zone. Within this classification, the Iranshahr, Zabul, and Bahuklat regions are specifically identified as having a desert climate, while Zahedan is situated at the intersection of desert and semi-desert climates. The Saravan, Khash, and Chabahar areas experience a semi-desert climate, whereas the

mountainous region of Bam Pusht, stretching south from Saravan to the Beshagard mountains, exhibits a moderate semi-desert climate. The eastern part of the province is characterized by a semi-desert climate with high altitudes and plateaus, including a small area that endures cold winters (Ministry of Jihad-e-Agriculture of Iran, 2022). Figure 1 illustrates the study area's location.



Figure 1. The location of study area in Iran.

For the study, sample of farmers from the province were selected using a systematic random sampling method. The sample ratio was determined by dividing the sample size by the total population size. The first sample was randomly chosen based on this ratio, and each subsequent sample was obtained by adding the same ratio to the previous selection. Cochran's correlation formula (1) was employed to calculate the appropriate sample size from the overall population (Cochran, 1977).

$$n = \frac{\frac{z^2 pq}{d^2}}{1 + \frac{1}{N}(\frac{z^2 pq}{d^2} - 1)} \quad (1)$$

The necessary sample size (n) for a study is influenced by the number of farms in the target population (N), the reliability coefficient (z) set at 1.96 for a 95% confidence level, the estimated proportion of a certain feature in the population (p) set at

0.5, the complementary proportion (q) also set at 0.5, and the allowed margin of error deviation from the mean population (d) set at 0.05.

Energy input-output analysis

Energy input-output analysis is a method used to assess the energy flows within an economy, examining how energy is generated, distributed, and consumed across various sectors. This approach relies on input-output tables, which detail the interrelationships among different industries and how they interact in terms of inputs and outputs (Kaab et al., 2024; Saadi et al., 2025). The primary aim of energy input-output analysis is to understand the direct and indirect energy use associated with the production of goods and services. It quantifies the energy requirements of various industries, allowing for a comprehensive examination of the entire economy's energy efficiency (Taherzadeh-Shalmai et al., 2023). By tracking the energy inputs needed for production processes, as

well as the resultant outputs, researchers can identify patterns of energy consumption, potential inefficiencies, and areas for improvement. Additionally, this analysis facilitates a better understanding of the environmental impact of different sectors by correlating energy use with emissions, resource depletion, and other ecological considerations (Ghasemi-Mobtaker et al., 2024). It can be particularly useful for

policymakers aiming to develop strategies for energy conservation, renewable energy integration, and the reduction of greenhouse gas emissions. Overall, energy input-output analysis provides valuable insights for sustainable economic planning and decision-making, allowing stakeholders to visualize the intricate web of energy dependencies within an economy. The energy equivalent of each input is detailed in Table 1.

Table 1. The coefficients of energy inputs and outputs in the production of wheat.

Items	Unit	Energy equivalent (MJ unit ⁻¹)	References
<i>A. Inputs</i>			
1. Human labor	h	1.96	(Mohammadi Kashka et al., 2023)
2. Machinery	kg yr ^a	62.70	(Kaab et al., 2023)
3. Diesel fuel	L	56.31	(Mohseni et al., 2018)
4. Chemical fertilizers	kg		
(a) Nitrogen		76.14	(Yang et al., 2022)
(b) Phosphate		12.40	(Ghasemi-Mobtaker et al., 2024)
(c) Potassium		11.15	(Kaab et al., 2023)
5. Biocides	kg	250	(Fnaies et al., 2022)
7. Electricity	kWh	12	(Al-Falahat et al., 2022)
8. Seed	kg	25.00	(Ingrao et al., 2018)
<i>B. Output</i>			
1. Wheat		25.00	(Ingrao et al., 2018)
2. Straw Wheat		12.50	(Ingrao et al., 2018)

^a The economic life of machine (year).

The energy performance of each planting system was assessed by examining various energy indicators, including energy ratio, efficiency, productivity, specific energy, and net energy efficiency. This analysis involved estimating the total input and output energies (Kaab et al., 2023). These indicators were utilized to explore the correlation between input and output energy per hectare, considering factors such as crop and soil types, tillage practices, application of chemical and livestock fertilizers, as well as storage, maintenance, and harvesting methods. Energy efficiency, quantified by Equation 2 as the ratio of energy input to energy output within the system, was particularly important in these evaluations (Ghasemi-Mobtaker et al., 2022).

In simpler terms, Equation 3 measures how much value is added by the energy input in producing goods and services, with a higher value indicating better efficiency (Taherzadeh-Shalmai et al., 2021). Equation 4, on the other hand, calculates the amount of

energy used for producing goods and services, helping to understand energy efficiency in production. These two equations are inversely related, meaning that a higher energy productivity index corresponds to lower energy intensity (Khalaj et al., 2023). Equation 5 defines net energy gain as the surplus energy obtained after subtracting input energy from total output energy, often used in optimizing energy production in agriculture, particularly for energy crops (Farvardin et al., 2024).

$$\text{Energy use efficiency} = \frac{\text{Output energy (MJ)}}{\text{Input energy (MJ)}} \quad (2)$$

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

$$\text{Specific energy} = \frac{\text{Input energy (MJ)}}{\text{Production (kg)}} \quad (4)$$

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

Results and discussion

Results of input-output energy

Table 2 presents the input and output energy metrics of two wheat production systems: Conventional and Conservation Tillage. The table breaks down various components influencing energy usage per hectare in each system. For human labor, Conventional Tillage requires 432.69 hours with an energy expenditure of 848.07 MJ ha⁻¹, while Conservation Tillage necessitates only 321.15 hours, resulting in a lower energy usage of 629.45 MJ ha⁻¹. A notable discrepancy is observed in machinery hours; Conventional Tillage demands 138.53 hours, translating to an energy consumption of 8685.83 MJ ha⁻¹, compared to Conservation Tillage's 100.23 hours and 6284.42 MJ ha⁻¹. In terms of diesel consumption, Conventional Tillage utilizes 85.52 liters, equating to 4815.63 MJ ha⁻¹, whereas Conservation Tillage consumes 62.25 liters, amounting to 3505.29 MJ ha⁻¹. Chemical fertilizers, a vital input, also show differences. Conventional Tillage applies 297 kg of nitrogen (22613.58 MJ), 263 kg of phosphate (3261.20 MJ), and 50.93 kg of potassium (567.87 MJ). In contrast, Conservation Tillage uses less: 230 kg of nitrogen (17512.20 MJ), 190 kg of phosphate (2356.00 MJ), and 41 kg of potassium (457.15 MJ). Additionally, biocides and electricity usage reflect contrasting trends. Conventional Tillage applies 2.35 kg of biocides resulting in 587.50 MJ ha⁻¹ energy use, while Conservation Tillage uses 2.00 kg with an energy expenditure of 500.00 MJ ha⁻¹. For electricity, Conventional Tillage consumes 125.63 kWh (1507.56 MJ) compared to 102.32 kWh (1227.84 MJ) for Conservation Tillage. The seed requirement is also higher in Conventional Tillage, using 269.03 kg and consuming 6725.75 MJ ha⁻¹ compared to 220.00 kg (5500.00 MJ) in Conservation Tillage. When aggregated, Conventional Tillage totals an energy input of 49612.99 MJ ha⁻¹, while Conservation Tillage significantly lowers this to 37972.36 MJ ha⁻¹. On the output side, Conventional Tillage produces 6120 kg of wheat seed, culminating in 153000 MJ of energy output, contrasted with Conservation Tillage, which yields 6500 kg and a higher energy output of

162500 MJ. Wheat straw production shows a slightly lower output in Conventional Tillage at 2850 kg (35625 MJ) compared to 3000 kg (37500 MJ) from Conservation Tillage. The total energy output sums up to 188625 MJ for Conventional Tillage and 200000 MJ for Conservation Tillage. In summary, the data indicates that Conservation Tillage utilizes less energy input while yielding higher outputs, positioning it as a potentially more sustainable and efficient method for wheat production. This research investigates power consumption in the Phaphamau region, particularly focusing on the sub-regions of Gangapar, Gomti-par, and Tarai, where factors like soil texture, agro-climatic conditions, and climate variations significantly impact energy use. The findings reveal variations in animal usage, tractor-drawn implement utilization, and energy consumption across different farm categories in the area. For instance, animal use peaks in Tarai among marginal farmers, while tractor-drawn implements are most utilized in Gangapar for large farmers. The motivation for this study arises from the increasing need for sustainable mechanization in agriculture, driven by climate change and unpredictable weather patterns (Ray et al., 2018). The rise in global temperatures and erratic climatic conditions pose challenges to traditional farming practices, resulting in reduced yields, soil degradation, and unsustainable energy consumption. Emphasizing a shift towards resilient and efficient agricultural systems is vital.

Table 2 underscores the pronounced distinctions in energy inputs and outputs between Conventional Tillage and Conservation Tillage, signaling opportunities for adopting more sustainable practices. The clear difference in energy consumption highlights Conservation Tillage's dual benefits of reducing total energy input while enhancing energy output—a critical factor amid growing climate stressors, where optimizing resource utilization can alleviate some negative impacts of climate variability. As energy costs remain volatile and the impacts of fossil fuel dependency become more evident, there is a pressing need for sustainable farming practices that lower energy consumption. The reduced

energy demands associated with Conservation Tillage—characterized by less labor, machinery use, and diesel fuel consumption—lead to lower operational costs. This is especially crucial for farmers in developing regions facing economic instability. Furthermore, decreased reliance on chemical fertilizers and biocides aligns with environmental sustainability goals by mitigating agricultural runoff, preserving soil health, and fostering biodiversity. Statistical evidence shows that Conservation Tillage not only requires fewer inputs but also yields higher wheat outputs, signaling its potential role in enhancing food security, particularly in adverse climatic conditions. With a rising

global population and increasing food demands, adopting sustainable practices like Conservation Tillage is essential for optimizing agricultural productivity. In conclusion, this study highlights an urgent need for sustainable agricultural practices capable of adapting to climate change and bolstering global food security. By providing substantial evidence advocating for the transition to Conservation Tillage, this research contributes to a transformative shift towards more resilient agricultural systems, ultimately promoting a sustainable future for farming in an unpredictable climatic environment.

Table 2. Input-output energy in different wheat production systems.

Items	Conventional Tillage		Conservation Tillage	
	Unit per ha	Energy use (MJ ha ⁻¹)	Unit per ha	Energy use (MJ ha ⁻¹)
1. Human labor (h)	432.69	848.07	321.15	629.45
2. Machinery (h)	138.53	8685.83	100.23	6284.42
3. Diesel fuel (L)	85.52	4815.63	62.25	3505.29
4. Chemical fertilizers (kg)				
(a) Nitrogen	297.00	22613.58	230.00	17512.20
(b) Phosphate (P ₂ O ₅)	263.00	3261.20	190.00	2356.00
(c) Potassium (K)	50.93	567.87	41.00	457.15
5. Biocides (kg)	2.35	587.50	2.00	500.00
6. Electricity (kwh)	125.63	1507.56	102.32	1227.84
7. Seed (kg)	269.03	6725.75	220.00	5500.00
Total energy use (MJ)	-	49612.99	-	37972.36
B. Output (kg)				
1. Wheat seed	6120.00	153000.00	6500.00	162500.00
2. Wheat straw	2850.00	35625.00	3000.00	37500.00
Total energy output (MJ)	-	188625.00	-	200000.00

Figure 2 illustrates the energy consumption linked to two distinct tillage practices: conventional tillage and conservation tillage. It quantifies the nitrogen inputs for each method, showing values of 45.58 for conventional tillage and 46.12 for conservation tillage, indicating a modest increase in nitrogen needs for the latter. Additionally, the figure reveals that machinery use and diesel fuel account for the largest share of energy consumption in wheat production. This highlights the importance of machinery in the planting, cultivating, and harvesting processes, as well as the fuel required to operate this equipment, in

determining the overall energy demands of wheat farming. Understanding these energy dynamics is essential for assessing the sustainability and efficiency of various agricultural practices. Intensive tillage boosts yields but raises energy use and carbon footprints, challenging sustainability. This study assessed energy, productivity, and emissions across conventional, deep, and no-tillage practices with/without straw mulch in maize-wheat systems. No-tillage with mulch significantly reduced energy input, enhanced yields, and minimized carbon emissions, proving the most efficient practice (Nisar et al., 2021).

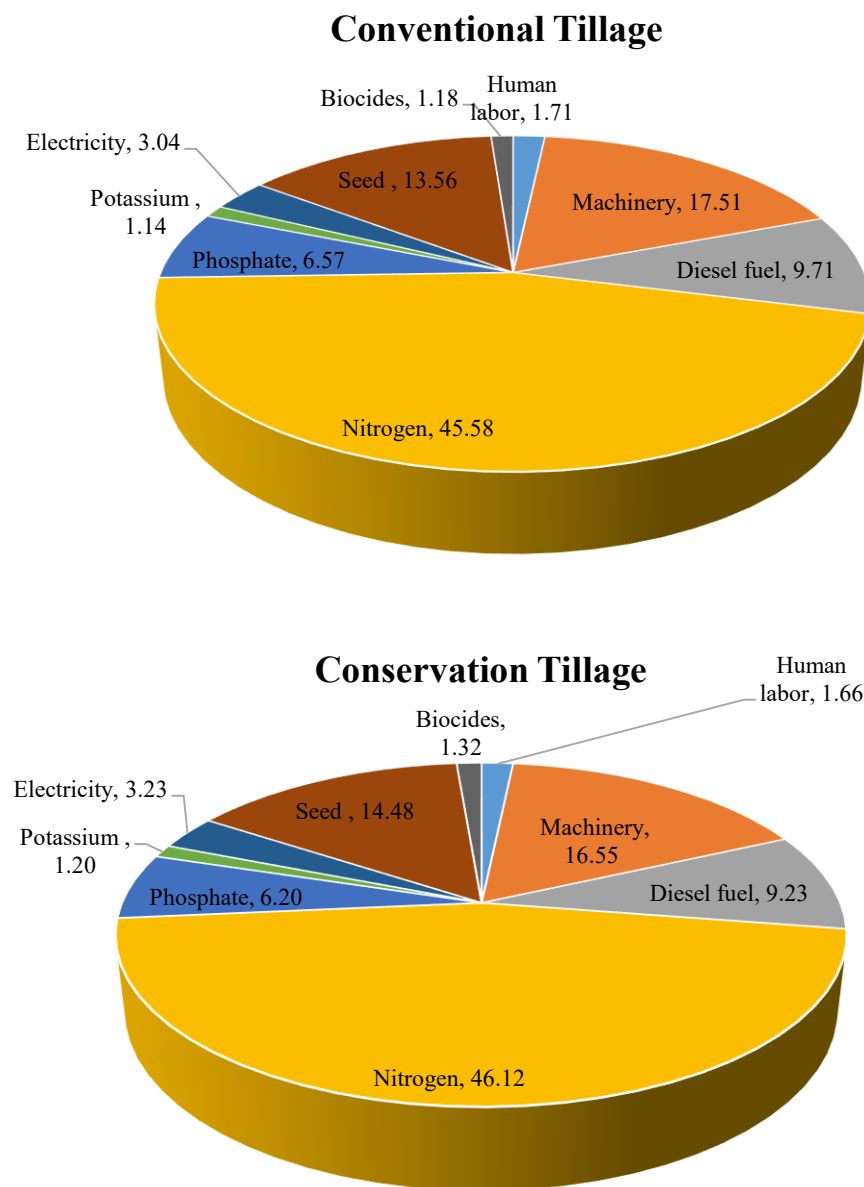


Figure 2. The impact of energy sources on different wheat production systems.

Based on the insights from Fig. 4 regarding energy consumption in different tillage practices, here are several recommendations for enhancing sustainability and efficiency in wheat farming:

1. Optimize machinery use: Since machinery operation and diesel fuel account for the highest energy consumption, farmers should prioritize optimizing machinery use. This could involve precision agriculture techniques to minimize unnecessary passes

over the field, reducing overall fuel consumption.

2. Explore alternative energy sources: Investigate the use of renewable energy sources, such as biodiesel or electric-powered machinery. Transitioning to alternative fuels could help decrease reliance on diesel and reduce the carbon footprint associated with conventional tillage practices.

3. Integrate conservation practices: Given the slight increase in nitrogen inputs for

conservation tillage, which may have other environmental benefits, farmers should weigh these inputs against the energy savings from reduced machinery use in conservation practices. Promoting cover cropping and reduced tillage could lead to better soil health and lower energy requirements over time.

4. Conduct Cost-Benefit analyses: A detailed analysis comparing the economic and environmental costs of conventional and conservation tillage practices is essential. This will help in understanding the long-term sustainability of these practices, considering the evolving energy dynamics.

5. Training and education: Providing farmers with training on energy-efficient practices and the benefits of conservation tillage can facilitate a shift towards more sustainable agricultural methods. Workshops and resources should be made available to assist in understanding best practices for machinery operation and energy consumption.

6. Invest in technology: Encourage investment in newer, more energy-efficient machinery and technologies that require less fuel and can perform multiple tasks, such as no-till drills or multi-purpose harvesters. These innovations can significantly reduce both energy consumption and nitrogen inputs over time.

7. Monitor and adapt practices: Continued monitoring of energy use and nitrogen inputs across different tillage practices should be encouraged. Adaptation of practices based on data and outcomes will help farmers optimize efficiency and sustainability in response to changing conditions.

By implementing these recommendations, wheat farmers can enhance their operational efficiency while minimizing environmental impacts, ultimately contributing to more sustainable agricultural practices.

Energy indicators

Table 3. Energy indices in wheat production systems.

Items	Conventional Tillage	Conservation Tillage
Energy use efficiency (ratio)	3.80	5.20
Energy productivity (kg MJ ⁻¹)	0.18	0.25
Specific energy (MJ kg ⁻¹)	5.53	3.99
Net energy gain (MJ ha ⁻¹)	139012.01	162027.63

Table 3 presents a comparison of energy indices in different wheat production systems, specifically conventional tillage and conservation tillage. In terms of energy use efficiency, the conventional tillage system has a ratio of 3.80, while the conservation tillage system shows a higher ratio of 5.20. This indicates that conservation tillage is more effective at converting energy inputs into outputs, leading to a more sustainable production system. Looking at energy productivity (kg MJ⁻¹) of energy consumed, the conventional tillage system shows a productivity of 0.18, whereas conservation tillage has a higher productivity of 0.25. This suggests that conservation tillage not only uses energy more efficiently but also produces more wheat per unit of energy input. Specific energy, which refers to the amount of energy required to produce a kilogram of wheat (MJ kg⁻¹), is lower in the conservation tillage system at 3.99 compared to 5.53 in the conventional tillage system. This means that, on average, less energy is needed to produce each kilogram of wheat in conservation tillage. Finally, net energy gain, reported in (MJ ha⁻¹), reflects the total energy produced minus the energy input. The conventional tillage system achieves a net energy gain of 139,012.01 MJ ha⁻¹, while conservation tillage sees a greater net energy gain of 162,027.63 MJ ha⁻¹. This highlights that conservation tillage not only uses energy more effectively but also results in a higher overall energy surplus, making it a more efficient and sustainable option in wheat production systems. Intensive tillage increases energy use, harming soil and environment. Conservation practices like reduced or no-tillage can enhance sustainability and profits. Six tillage methods were assessed: CT, CTB, RT, RTB, ZT, and ZTB. Results showed significant energy savings with reduced tillage, while RT and ZT offered higher energy productivity. RT was better for wheat, but less effective for maize, requiring further study (Iqbal et al., 2024).

Research findings

The research findings provide a comprehensive comparison of energy metrics between Conventional Tillage and Conservation Tillage systems in wheat production, emphasizing the significant differences in energy consumption and outputs. Conventional Tillage is characterized by higher energy inputs across various components, including human labor, machinery operation, diesel fuel consumption, and chemical fertilizers, leading to a total energy input of 49,612.99 MJ ha⁻¹. In contrast, Conservation Tillage demonstrates a marked reduction in energy input, totaling 37,972.36 MJ ha⁻¹, while simultaneously achieving higher energy outputs, with wheat production yielding 6,500 kg and an energy output of 162,500 MJ compared to Conventional Tillage's 6,120 kg and 153,000 MJ. The analysis reveals that Conventional Tillage requires more labor hours (432.69 hours) and machinery hours (138.53 hours), translating to higher energy expenditures (848.07 MJ ha⁻¹ for labor and 8,685.83 MJ ha⁻¹ for machinery). Diesel consumption also reflects this trend, with Conventional Tillage utilizing 85.52 liters (4,815.63 MJ ha⁻¹) compared to 62.25 liters (3,505.29 MJ ha⁻¹) in Conservation Tillage. The disparities extend to chemical fertilizers, where Conventional Tillage applies 297 kg of nitrogen, 263 kg of phosphate, and 50.93 kg of potassium, resulting in higher energy costs than the lower inputs used in Conservation Tillage (230 kg nitrogen, 190 kg phosphate, and 41 kg potassium). The findings underscore the efficiency of Conservation Tillage, which not only requires less energy input but also produces higher outputs, making it a more sustainable and effective method for wheat production. This efficiency is further reflected in the energy indices presented in Table 3, where Conservation Tillage exhibits a higher energy use efficiency ratio (5.20 compared to 3.80 for Conventional Tillage) and greater energy productivity (0.25 kg MJ⁻¹ versus 0.18 kg MJ⁻¹). Specific energy requirements are also lower in Conservation Tillage (3.99 MJ kg⁻¹) compared to Conventional Tillage (5.53 MJ kg⁻¹), indicating that less energy is needed to produce each kilogram of wheat. Moreover,

the net energy gain is significantly greater in Conservation Tillage, with a reported 162,027.63 MJ ha⁻¹ versus 139,012.01 MJ ha⁻¹ for Conventional Tillage. These findings highlight the potential for Conservation Tillage to enhance food security while minimizing environmental impacts, especially in the context of climate change and the need for sustainable agricultural practices. The research also delves into regional variations in energy consumption linked to different farming practices in the Phaphamau region, where factors such as soil texture and agro-climatic conditions influence energy use. It identifies the necessity for sustainable mechanization in agriculture, particularly in response to the challenges posed by climate change, including reduced yields and soil degradation. To further promote sustainable practices, several recommendations are proposed. These include optimizing machinery use through precision agriculture, exploring alternative energy sources, integrating conservation practices, conducting cost-benefit analyses, providing training and education for farmers, investing in more energy-efficient technology, and continuously monitoring and adapting practices based on data. By implementing these strategies, wheat farmers can improve operational efficiency and reduce environmental impacts, contributing to a more sustainable agricultural future. In conclusion, the study emphasizes the critical need for a transition toward Conservation Tillage practices to enhance resilience in agricultural systems, particularly in the face of climate variability and increasing food demands. The substantial evidence presented advocates for adopting more sustainable practices, ultimately supporting a transformative shift in farming toward a more sustainable future.

Conclusions

This study highlights the essential role of wheat (*Triticum* spp.) as a vital staple crop for global food security and sustainable agriculture. It specifically examines the energy inputs and outputs associated with two tillage systems: conventional tillage and conservation tillage, focusing on the Sistan

and Baluchistan Province. The findings reveal marked differences in energy consumption between these methods. Conventional tillage requires an energy input of 49,612.99 MJ ha⁻¹, while conservation tillage only requires 37,972.36 MJ ha⁻¹, showcasing the superior energy efficiency of conservation practices, which achieve an energy use efficiency ratio of 5.20 compared to 3.80 for conventional tillage. Moreover, the analysis indicates that conservation tillage reduces the demand for labor, machinery, and chemical fertilizers and biocides, paving the way for a more sustainable wheat production approach. Based on these results, it is advised that farmers in Sistan and Baluchistan adopt conservation tillage methods. Such a transition can enhance energy efficiency, lower production costs, and lessen environmental impacts. Policymakers should promote awareness and develop training programs centered on conservation tillage strategies to support this shift. Additionally, research institutions must engage in studies assessing the long-term gains of conservation tillage and create support initiatives to encourage farmers toward sustainable practices. The significant differences in energy inputs and outputs between the two tillage systems reveal opportunities for adopting more sustainable agricultural practices. The reduced energy needs associated with conservation tillage lead to lower operational costs, which is particularly beneficial for farmers in developing regions facing economic hurdles. Additionally, a decreased reliance on chemical fertilizers and biocides aligns with environmental sustainability goals, reducing agricultural runoff and promoting soil health. Evidence suggests that conservation tillage requires fewer inputs while yielding higher wheat outputs, strengthening its role in enhancing

food security, especially under adverse climatic conditions. With a growing global population and increasing food demands, embracing sustainable practices like conservation tillage is crucial for optimizing agricultural productivity. In conclusion, this study underscores the pressing need for sustainable agricultural practices capable of adapting to climate change and enhancing global food security. The evidence supporting a shift to conservation tillage contributes to a transformative movement toward more resilient agricultural systems, fostering a sustainable future amid changing climatic conditions. To enhance sustainability and efficiency in wheat farming, recommendations include optimizing machinery use, exploring alternative energy sources, integrating conservation practices, conducting cost-benefit analyses, providing farmer training and education, investing in technology, and implementing monitoring strategies based on data-driven results. By applying these strategies, wheat farmers can boost operational efficiency while minimizing environmental impacts, ultimately fostering more sustainable agricultural practices. Furthermore, a comparison of energy indices across various wheat production systems shows that conservation tillage not only uses energy more efficiently but also generates a higher overall energy surplus, affirming its status as a more sustainable option for wheat production. The findings of this research underscore the critical importance of transitioning to conservation tillage to improve energy efficiency and sustainability in wheat farming.

Conflict of interest:

The authors declare that they have no conflict of interest.

References

- Ahmad, N., Sinha, D.K., and Singh, K.M. 2018. Productivity and Resource Use Efficiency in Wheat: A Stochastic Production Frontier Approach. *Economic Affairs*. 63(3), 611-616.
- Al-Falahat, A.M., Qadourah, J.A., Alrwashdeh, S.S., khater, R., Qatlama, Z., Alddibs, E., and Noor, M. 2022. Energy performance and economics assessments of a photovoltaic-heat pump system. *Results in Engineering*. 13, 100324.
- Alhajj Ali, S., Tedone, L., and De Mastro, G. 2013. A comparison of the energy consumption of rainfed durum wheat under different management scenarios in southern Italy. *Energy*. 61, 308–318.

- Cochran, W.G., 1977. The estimation of sample size. *Sampl. Tech.* 3, 72–90.
- Farvardin, M., Taki, M., Gorjian, S., Shabani, E., and Sosa-Savedra, J.C. 2024. Assessing the Physical and Environmental Aspects of Greenhouse Cultivation: A Comprehensive Review of Conventional and Hydroponic Methods. *Sustainability*. 16(3), 1273.
- Fnaïs, A., Rezgui, Y., Petri, I., Beach, T., Yeung, J., Ghoroghi, A., and Kubicki, S. 2022. The application of life cycle assessment in buildings: challenges, and directions for future research. *The International Journal of Life Cycle Assessment*. 27(5), 627-654.
- Ghasemi-Mobtaker, H., Ataiee, F.S., Akram, A., and Kaab, A., 2024. Feasibility study of using photovoltaic cells for a commercial hydroponic greenhouse: Energy analysis and life cycle assessment. *e-Prime-Advances in Electrical Engineering, Electronics and Energy*. 8, 100597.
- Ghasemi-Mobtaker, H., Kaab, A., Rafiee, S., and Nabavi-Pelesaraei, A. 2022. A comparative of modeling techniques and life cycle assessment for prediction of output energy, economic profit, and global warming potential for wheat farms. *Energy Reports*. 8, 4922–4934.
- Ingrao, C., Licciardello, F., Pecorino, B., Muratore, G., Zerbo, A., and Messineo, A. 2018. Energy and environmental assessment of a traditional durum-wheat bread. *Journal of Cleaner production*. 171, 1494-1509.
- Iqbal, J., Khaliq, T., Ahmad, A., Khan, K.S., Haider, M.A., Ali, M.M., Ahmad, N., and Rehmani, M.I.A. 2024. Productivity, profitability and energy use efficiency of wheat-maize cropping under different tillage systems. *Farming System*. 2(3), 100085.
- Kaab, A., Ghasemi-Mobtaker, H., and Sharifi, M. 2023. A study of changes in energy consumption trend and environmental indicators in the production of agricultural crops using a life cycle assessment approach in the years 2018-2022. *Iranian Journal of Biosystems Engineering*. 54(3), 1-18.
- Kaab, A., Ghasemi-Mobtaker, H., and Taherzadeh-Shalmai, N. 2023. Analysis of the Factors Affecting Field Waste from Sugarcane Harvesting. *Journal of Agricultural Mechanization*. 7(4), 11-15.
- Kaab, A., Khanali, M., Shadamanfar, S., and Jalalvand, M. 2024. Assessment of energy audit and environmental impacts throughout the life cycle of barley production under different irrigation systems. *Environmental and Sustainability Indicators*. 22, 100357.
- Khalaj, M., Gholami Parashkoochi, M., and Mohammad Zamani, D. 2023. Use of life cycle assessment and modeling techniques for prediction of energy-environmental indicators in different wheat production systems. *Environmental and Sustainability Indicators*. 18, 100237.
- Khan, Muhammad Azam, Khan, S., Khan, M A, and Latif, N. 2010. Energy requirements and economic analysis of wheat, rice and barley production in Australia Introduction of Rain Water Harvesting in a remote area of Dera Ismail Khan District of Pakistan. *View project Energy requirements and economic analysis of wheat, Soil and Environment*. 29(1), 61-68.
- Kumar, R., Sarkar, B., Bhatt, B.P., Mali, S.S., Mondal, S., Mishra, J.S., Jat, R.K., Meena, R.S., Anurag, A.P., and Raman, R.K. 2021. Comparative assessment of energy flow, carbon auditing and eco-efficiency of diverse tillage systems for cleaner and sustainable crop production in eastern India. *Journal of Cleaner Production*. 293, 126162.
- Ministry of Jihad-e-Agriculture of Iran, 2022. Annual Agricultural Statistics. www.maj.ir (in Persian).
- Mohammadi Kashka, F., Tahmasebi Sarvestani, Z., Pirdashti, H., Motevali, A., Nadi, M., and Valipour, M. 2023. Sustainable Systems Engineering Using Life Cycle Assessment: Application of Artificial Intelligence for Predicting Agro-Environmental Footprint. *Sustainability*. 15(7), 6326.
- Mohseni, P., Borghei, A.M., and Khanali, M. 2018. Coupled life cycle assessment and data envelopment analysis for mitigation of environmental impacts and enhancement of energy efficiency in grape production. *Journal of cleaner production*. 197, 937-947.
- Nisar, S., Benbi, D.K., and Toor, A.S. 2021. Energy budgeting and carbon footprints of three tillage systems in maize-wheat sequence of north-western Indo-Gangetic Plains. *Energy*. 229, 120661.
- Pourmehdi, K., and Kheiralipour, K., 2024. Net energy gain efficiency, a new indicator to analyze

- energy systems, case study: Comparing wheat production systems. *Results in Engineering*. 22, 102211.
- Pourmehdi, K., and Kheiralipour, K. 2023. Compression of input to total output index and environmental impacts of dryland and irrigated wheat production systems. *Ecological Indicators*. 148, 110048.
- Ray, A., Kumar, A., Rai, A., and Tripathi, S. 2018. Farm Mechanization and Energy Consumption for Different Farm Categories of Phaphamau Region. *Trends Biosci*, 11, 4419-35.
- Saadi, H., Behnia, M., Taki, M., and Kaab, A. 2025. A comparative study on energy use and environmental impacts in various greenhouse models for vegetable cultivation. *Environmental and Sustainability Indicators*. 25, 100553.
- Saglam, R., Seven, L., and Kup, F. 2020. Comparative analysis of energy input-outputs of different tillage methods in second crop corn production. *Notulae Scientia Biologicae*. 12(2), 356-365.
- Soltani, A., Rajabi, M.H., Zeinali, E., and Soltani, E. 2013. Energy inputs and greenhouse gases emissions in wheat production in Gorgan, Iran. *Energy*. 50, 54–61.
- Taherzadeh-Shalmai, N., Rafiee, M., Kaab, A., Khanali, M., Vaziri Rad, M.A., and Kasaeian, A. 2023. Energy audit and management of environmental GHG emissions based on multi-objective genetic algorithm and data envelopment analysis: An agriculture case. *Energy Reports*. 10, 1507–1520.
- Taherzadeh-Shalmai, N., Sharifi, M., Ghasemi-Mobtaker, H., and Kaab, A. 2021. Evaluating the energy use, economic and environmental sustainability for smoked fish production from life cycle assessment point of view (case study: Guilan Province, Iran). *Environmental Science and Pollution Research*. 28(38), 53833-53846.
- Yang, Z., Zhu, Y., Zhang, J., Li, X., Ma, P., Sun, J., Sun, Y., Ma, J., and Li, N. 2022. Comparison of energy use between fully mechanized and semi-mechanized rice production in Southwest China. *Energy*. 245, 123270.

