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Material and Energy Flow Cost Accounting of Sugar Beet Production in Iran: Enhancing Sustainability and Economic Viability

Rahim YarAhmadi[1], Esfandiar Fateh[*1], Majid Dekamin[2], Mohammad Saeed Hasanvandi[3]

[1]Department of Production Engineering and Plant Genetics, Faculty of Agriculture, Shahid Chamran University of Ahvaz, Ahvaz, Iran
[2]Department of Plant Production and Genetics, Faculty of Agriculture, Malayer University, Malayer, Iran
[3]Sugar Beet Research Department, Safiabad Agricultural and Natural Resources Research and Education Center, Agricultural Research, Education and Extension Organization (AREEO), Dezful, Iran

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ABSTRACT

This study evaluates the production of sugar beet in Iran, focusing on material and energy flow costs to identify critical points of high energy consumption and costs to enhance production sustainability. The Material and Energy Flow Cost Accounting (MEFCA) method, in line with ISO 14051 standards, was used for this analysis. Data were collected from sugar beet farms during the 2022-2023 agricultural year, covering all production stages from pre-planting to harvest. One hectare was considered as the functional unit, and all inputs and outputs were assessed based on this unit. The average energy input to sugar beet agro-ecosystems was 52,410 MJ ha^{-1}. Energy losses, due to factors like irrigation water wastage, crop losses, and pesticide use, totaled 102,201 MJ ha^{-1}. In contrast, the positive energy output from the harvested crop was 1,243,200 MJ ha^{-1}. Over 99% of energy losses were linked to sugar beet loss during harvest. Energy indicators, including energy productivity (1.41 kg MJ^{-1}), energy ratio (21.77), net energy (1,088,589 MJ), and specific energy (0.71 kg MJ^{-1}), were calculated. Average production costs amounted to $1,192 ha^{-1}, with a gross production value of $4,651 ha^{-1}, resulting in a net income of $3,458 ha^{-1} and a benefit-cost ratio of 3.9. Labor costs accounted for the highest share of production expenses. Sugar beet production in Iran remains economically and energetically viable, provided that subsidies for energy carriers and other inputs are maintained. Based on these findings, several strategies to improve sustainability and optimize sugar beet production are suggested, including reducing harvest losses through improved harvesting techniques and advanced machinery, optimizing energy use through efficient irrigation practices, minimizing pesticide application, managing labor costs via automation of specific processes, and investing in research and development to introduce innovative technologies.

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1. Introduction

With the growing global population, the demand for energy, water, and food is increasing dramatically, while land resources face significant limitations in meeting these rising needs (Aznar-Sánchez *et al.*, 2020). The current economic model, characterized by the principle of "take, make, use, and dispose," must be replaced with a model of "prevent, reuse, restore, and recycle" (Papamichael *et al.*, 2022). Although the implementation of modern agricultural methods has accelerated productivity growth, these practices often lead to excessive resource consumption and unsustainable energy use (Dekamin *et al.*, 2024a; Rodríguez-Espinosa *et al.*, 2023). To achieve a more sustainable future, environmental threats such as pollution, climate change, and biodiversity loss must be addressed. Estimates suggest that by 2050, the need for food production will increase by 1.5 billion tons (Willett *et al.*, 2019).

Since agricultural ecosystems are the primary source of food supply, this issue places considerable pressure on them (Rodríguez-Espinosa *et al.*, 2023). Approximately 90 billion tons of primary resources are extracted and consumed globally each year, of which

* Corresponding author.
E-mail address: e.fateh@scu.ac.ir

only 10% are recycled. At the same time, the agricultural sector accounts for about 70% of the world's freshwater withdrawals and nearly 31% of greenhouse gas emissions, making it a significant contributor to climate change (Aznar-Sánchez *et al*., 2020). Moreover, in 2019, agriculture and the food sector accounted for the second-largest material footprint, with 21.3 billion tons, and a carbon footprint of 10 billion tons of CO_2 emissions (Velasco-Muñoz *et al*., 2022). Intensive agriculture, through the use of chemical fertilizers, has degraded soil quality due to the accumulation and loss of nitrogen, phosphorus, and heavy metals, leading to water pollution, reduced soil productivity, and decreased soil biodiversity (de Vries *et al*., 2022).

The use of chemical fertilizers has increased from about 12 million tons in 1961 to over 110 million tons in 2018. Currently, nitrogen and phosphorus consumption has doubled the permissible limits, posing a major challenge to sustainability in agriculture and leading to risks of nitrate and ammonia pollution (Springmann *et al*., 2023; Steffen *et al*., 2015). ISO 14051, "Material Flow Cost Accounting (MFCA)" is a tool that, unlike other environmental management tools such as life cycle assessment, economically quantifies environmental impacts to convince producers of the economic benefits of reducing waste and production losses (Bierer *et al*., 2015). This tool has been applied in various studies, such as in the evaluation of the textile industry (Dechampai *et al*., 2021), healthcare services (Arieftiara *et al*., 2021), wastewater treatment (Ho *et al*., 2021), the hospitality sector (Nyide, 2016), and the meat industry (Bux and Amicarelli, 2022). Unlike other environmental management tools, MFCA links environmental and economic aspects at the producer level, providing a precise picture of production processes and waste, thereby becoming an effective tool for resource optimization (Kokubu and Kitada, 2015).

By quantifying waste in monetary units, this tool helps improve resource efficiency by reducing production costs (Bierer *et al*., 2015). In the agricultural and food sectors, MFCA has been applied to a more limited extent. Examples include assessments of blackberry juice production (Walz and Günther, 2021), soybean (Dekamin and Barmaki, 2019), grapes (Dekamin and Barmaki, 2019), corn (Afshar and Dekamin, 2022), canola (Dekamin, 2021), coriander (Dekamin *et al*., 2022), viticulture systems (Dekamin *et al*., 2024a) and greenhouse crops (Dekamin *et al*., 2024b). This study introduces a comprehensive evaluation of the material and energy flow costs in sugar beet production in Iran, utilizing the Material and Energy Flow Cost Accounting (MEFCA) method in accordance with ISO 14051 standards. Unlike previous studies that primarily focus on environmental or economic aspects separately, this research integrates both to assess the sustainability of the production process. By calculating energy indicators and analyzing the energy and cost-intensive stages, the study provides insights into optimizing agricultural practices and reducing waste in sugar beet production. The integration of economic data with energy flows highlights the interdependencies between production efficiency and environmental impact, offering a novel approach to improving both financial and environmental outcomes in agricultural systems. The primary objective of this study is to evaluate the material and energy flow costs in sugar beet production in northern Khuzestan, Iran, with a focus on identifying energy-intensive and high-cost areas to improve production sustainability. The study aims to quantify energy inputs, losses, and outputs, as well as calculate key energy indicators such as energy productivity, energy ratio, and net energy. Another objective is to analyze the economic viability of sugar beet production by assessing production costs, gross value, net income, and benefit-cost ratios. Based on these findings, the study seeks to propose practical strategies for reducing energy consumption, optimizing resource use, and mitigating environmental impacts in sugar beet production, ultimately contributing to the sustainable development of the agricultural sector in Iran.

2. Materials and methods

2.1. Material flow cost accounting (MFCA)

Material Flow Cost Accounting (MFCA) is recognized as a tool for managing green productivity (Wagner, 2015). By providing recommendations for reducing the use of materials, energy, and human resources, MFCA contributes to enhancing production efficiency. As stated in the ISO 14051 standard, MFCA quantifies system inputs and outputs in terms of energy and monetary units (Afshar and Dekamin, 2022). Compared to traditional material and cost accounting methods, MFCA isolates and calculates the costs and energy associated with resources such as energy, water, materials, and losses in the production process (e.g., the cost of fertilizer loss, irrigation water, and crop losses during harvesting). In other words, it uncovers hidden costs and losses in the production process (Kokubu and Kitada, 2015; Nishitani *et al*., 2022). MFCA can be effectively applied in the agricultural sector to identify and quantify hidden costs related to material flows throughout farming processes. This standard focuses on tracking the use of resources such as raw materials (e.g., seeds, fertilizers, pesticides), water, energy, and the generation of waste (e.g., crop residues, by-products), providing a clear picture of material efficiency in agricultural production. In traditional agricultural cost accounting systems, indirect costs such as waste, unused resources, or energy inefficiencies are often overlooked or generalized. However, MFCA enables a more detailed and specific analysis of how materials are used and where losses occur. By tracking the flow of materials from planting to harvest, including those that are lost as waste, by-products, or inefficiencies, farmers and agricultural producers can uncover hidden costs that would otherwise remain undetected.

In the context of ISO 14051 applied to sugar beet production, products are classified into "positive" products and "negative" products to better assess the flow of materials and identify inefficiencies or hidden costs in sugar beet production. This classification helps farmers and agricultural producers understand how resources are used, where losses occur, and how to optimize their processes for both economic and environmental benefits. In the ISO 14051 standard, also known as Material Flow Cost Accounting (MFCA), waste (i.e. Negative product) is generally categorized into three main types. This classification helps to identify specific sources of waste and optimize processes more effectively. These categories are as follows:

2.1.1. Material

This category refers to the losses of raw materials that occur during production or processing, typically due to inefficiencies or suboptimal usage. In agriculture, material losses may include product waste, damage to crops, or the inefficient use of chemicals such as fertilizers and pesticides. These losses often result from inadequate handling or processing techniques, leading to unnecessary material consumption.

2.1.2. Energy

This category includes the waste of energy resources that occur when more energy than necessary is consumed or when energy is lost during the production process. In agricultural production, energy losses may arise from the excessive use of machinery, irrigation systems, or post-harvest processing activities such as drying or storage. Such inefficiencies can lead to higher production costs and lower overall energy efficiency.

2.1.3. Environmental

This category addresses waste that negatively impacts the environment. It includes the loss of natural resources and environmental pollutants resulting from agricultural activities. In the agricultural sector, environmental losses may include the overuse of water, the release of pollutants from excessive use of chemicals (such as fertilizers or pesticides), and improper disposal of waste or by-products. These losses not only increase costs but also contribute to environmental degradation. By categorizing waste into these three types, ISO 14051 helps agricultural producers pinpoint inefficiencies at each stage of the production process. Identifying material, energy, and environmental losses allows farmers and producers to implement targeted measures for waste reduction, improve resource efficiency, and lower both production costs and environmental impact. The five stages of MFCA are illustrated in Fig. 1. During the production process, losses and negative outputs (including emissions to air, water, and soil, as well as waste) are evaluated in monetary and energy terms. Subsequently, recommendations are made to reduce negative losses and increase positive outputs (the intended product).

2.1.4. Responsibilities and farmer considerations

Given the rising costs of agricultural inputs, opportunity costs, and the instability in the purchasing prices for agricultural produce, it has become increasingly important to adopt efficient accounting methods to ensure the economic sustainability of agricultural systems. In this context, Material Flow Cost Accounting (MFCA) stands out as a crucial tool for evaluating the efficiency and sustainability of agricultural production, particularly in the case of sugar beet cultivation in northern Khuzestan. The region is known for its significant contribution to sugar beet production in Iran, yet it faces several challenges related to rising input costs, fluctuating market prices, and the need to optimize resource use in a sustainable manner. The research team was responsible for collecting data, monitoring processes, reviewing and analyzing results, and providing the best strategies for economically sustainable sugar beet production.

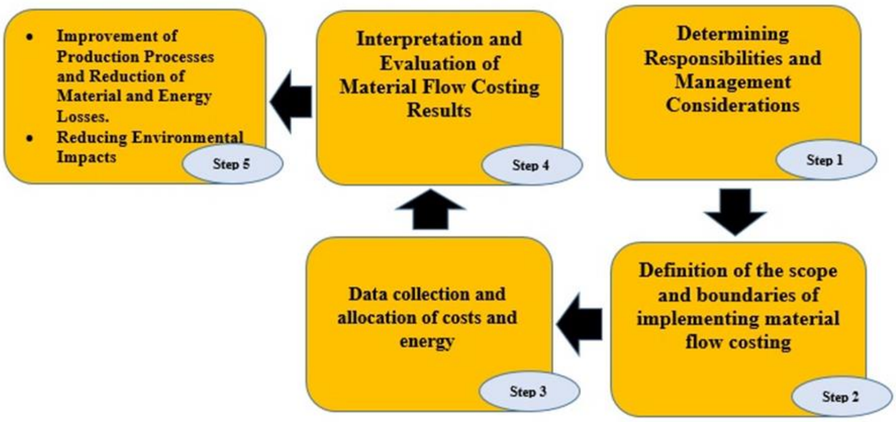

Figure 1. Material flow cost accounting based on ISO 14051 (Sahu *et al*., 2021)

2.1.5. Selecting the scope and objective of the MFCA study

Determining the scope and objective of a Material Flow Cost Accounting (MFCA) study is essential for ensuring that the methodology is effectively implemented to address the specific challenges faced by the production system. The success of the study largely depends on the clear definition of these parameters, as they guide the entire research process and help focus efforts on the most impactful areas of the production system. In the case of sugar beet production in northern Khuzestan, setting a precise scope and objective allowed for a targeted approach to identifying inefficiencies and improving sustainability. The primary objective of this research was to identify critical cost and energy loss points (often referred to as "hot spots") in the sugar beet production process. These hot spots are areas where material or energy is being lost at an unsustainable rate, leading to higher costs, reduced efficiency, and potential environmental damage. By pinpointing these areas, the study aimed to help farmers and agricultural stakeholders take corrective actions to improve overall resource efficiency. Identifying hot spots is critical not only for cost reduction but also for enhancing the energy productivity of the farming system, ultimately contributing to the sustainability of sugar beet production in the region. By applying MFCA, the study sought to create a comprehensive view of material and energy flows at the farm level, with the ultimate goal of offering actionable recommendations for improving both economic and environmental performance. The study's findings are expected to provide insights into how resource use can be optimized, energy losses can be reduced, and costs can be minimized, all of which are crucial for improving profitability and ensuring that sugar beet production remains competitive in the long term.

2.1.6. Functional unit, system boundary, and data collection

The accuracy and relevance of the results from Material Flow Cost Accounting (MFCA) depend heavily on two key factors: the functional unit (FU) and the system boundary (SB). These elements are crucial for defining the scope and scale of the study, ensuring that the inputs, outputs, and processes are measured consistently and meaningfully. Properly defining the FU and SB allows for an in-depth analysis of material and energy flows, helping to identify inefficiencies and optimize resource use. The functional unit (FU) serves as the baseline for measuring and evaluating all material and energy inputs and outputs within the system. It provides a standardized reference that allows for comparisons and accurate assessments of resource use, energy efficiency, and economic performance. In agricultural production, the FU is typically defined in terms of mass (e.g., tons of crops) or area (e.g., per hectare of land). For this study, the FU was defined as the production of sugar beet per 1 hectare. By setting the FU to 1 hectare, the study ensures that the results are consistent and directly comparable, as the material and energy inputs, outputs, and costs are all calculated on a per-hectare basis. This approach facilitates the evaluation of input quantities and outputs throughout the production cycle and helps identify key areas where efficiency improvements can be made. It's important to note that infrastructure costs, such as those related to land, irrigation systems, and maintenance, were excluded from this study's analysis. However, all production-related costs, such as fertilizers, pesticides, labor, water usage, and energy inputs, were considered. These factors contribute directly to the material and energy flows analyzed in the MFCA.

2.1.7. System boundary

The system boundary (SB) defines the limits of the analysis, specifying the points within the production process where data should be collected and how the system is modeled. This boundary is essential for focusing the study on the relevant stages of the sugar beet production cycle, ensuring that data is collected where it will yield the most meaningful insights. In this study, the SB encompasses all the key stages of sugar beet production, from land preparation and planting to harvesting (Fig. 2). The MFCA methodology also includes the evaluation of material and energy losses during these stages, with a particular emphasis on areas where inefficiencies are likely to occur, such as irrigation, fertilization, pesticide use, and harvesting.

One distinctive feature of MFCA, compared to other environmental management tools, is its ability to assign economic and energy values to environmental emissions. By including emissions such as CO_2, nitrogen oxide, and other pollutants, MFCA provides a comprehensive understanding of both the economic and environmental implications of farming practices. Furthermore, MFCA focuses on emissions that can be controlled or reduced by the farmer, such as energy inefficiencies, water wastage, or overuse of chemicals. This allows for material and energy losses to be transformed into positive outputs, which not only reduce costs but also improve the environmental performance of the agricultural system.

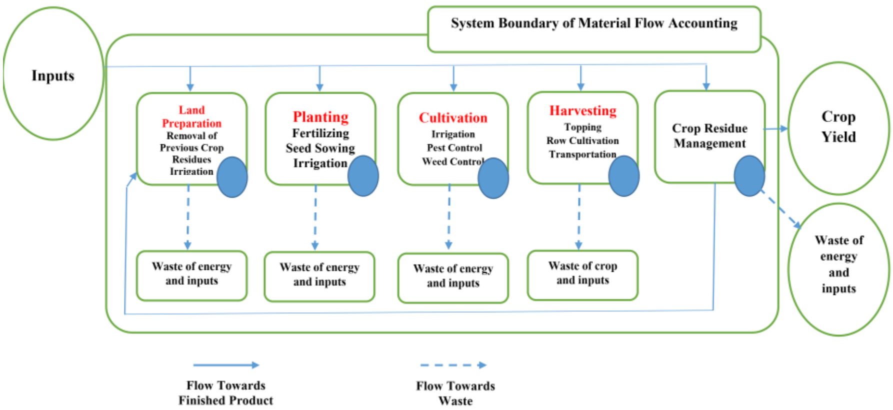

Figure 2. System boundary of the sugar beet production system

2.1.8. Data collection

Data collection is a critical step in the MFCA process. A detailed inventory list is required to map the flows of materials and energy throughout the production process. This inventory includes the following elements:

- Energy carriers (e.g., diesel fuel, electricity)
- Inputs (e.g., fertilizers, pesticides, irrigation water)
- Emissions to water, soil, and air (e.g., CO_2 emissions, chemical runoff)

The data collected are crucial for assessing both the environmental impact and economic performance of the production process. Accurate and comprehensive data is essential for calculating energy and material losses, as well as determining the costs and energy values of environmental emissions.

Data collection for this study was carried out through direct interviews and the use of questionnaires. These methods were employed to gather primary data from sugar beet farmers about various aspects of their production process. The data were collected from the northern part of Khuzestan province. The location of the data collection site is shown in Fig. 3. The data collected included key agricultural variables such as:

- Cultivated area: The total area of land dedicated to sugar beet cultivation in the selected fields.
- Agricultural input variables: Detailed information on the quantities of various inputs used during production, including:
    - Fertilizers: Types and amounts of fertilizers applied to the crops.
    - Pesticides: Usage patterns and amounts of pesticides employed.
    - Irrigation water: The volume and methods of water used for irrigation.
- Sugar beet yield: The total amount of sugar beet produced, measured in tons per hectare.
- Machinery and equipment: Information on the types of machinery used in planting, cultivating, and harvesting sugar beet, as well as any associated energy consumption.

The data were randomly collected from various sugar beet fields throughout northern Khuzestan during the 2022-2023 agricultural year. This random sampling method ensures that the data collected is representative of the broader sugar beet farming practices in the region, avoiding biases that could arise from focusing on particular farms or areas (Table 1). By collecting data from a diverse set of farms, the study captures a comprehensive view of the agricultural practices, energy use, and material flows associated with sugar beet production.

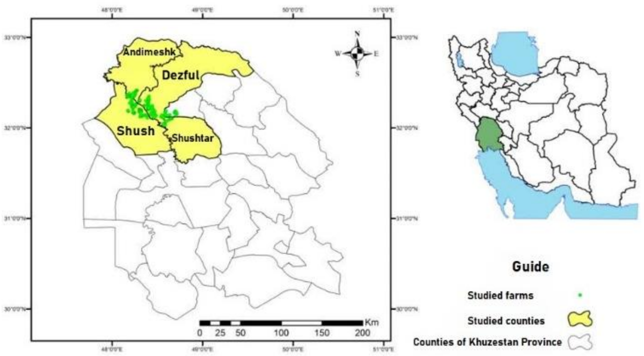

Figure 3. Map of the distribution of the studied sugar beet fields

Table 1. Sampling methodology and population parameters for sugar beet production analysis in northern Khuzestan (2022–2023)

Crop	Population size	Sample size based on cochran's formula	Number of units studied
Sugar beet	205	133.9	140

On the other hand, various formulas were used to calculate the input losses involved in the production process that have both economic and energy values. The main losses included chemical fertilizers, irrigation water, pesticides, and crop losses during harvest or throughout the production process. All these losses were calculated based on the coefficients provided in Table 2. Fertilizer losses to water, air, and soil were also taken into account. In this study, the PestLCI 2.0 model was used to calculate the emissions of pesticides to water and air. This model provides a modeled inventory list for calculating the emissions of fungicides, insecticides, and herbicides from the environment (ecosphere) to agricultural lands (technosphere), which is used in environmental impact modeling of production (Renaud-Gentié *et al*., 2015). The chemical transformation of nitrogen fertilizers from urea to ammonia causes a portion of the energy contained in them to be lost. To accurately calculate this lost energy, a concept called standard enthalpy of formation was used. This concept helps us determine the amount of energy stored in each chemical compound. By comparing the standard enthalpy of formation of urea and ammonia, the exact amount of energy released in the process of converting urea to ammonia can be calculated (Table 2).

Table 2. Fertilizers emissions standard enthalpy of formation (Afshar and Dekamin, 2022)

Emissions type	Molar mass (g mole^{-1})	Molar mass eq. (kJ mole^{-1})	Energy eq. (MJ kg^{-1})
N_2O	44	82.5	1.88
NH_3	17.03	46	2.70
NO_3	62	206	3.32

The calculation of input losses in the production process is a critical component of the Material Flow Cost Accounting (MFCA) methodology. These losses, which include both economic and energy values, are essential for identifying inefficiencies and improving sustainability in agricultural practices. The main losses considered in this study include those related to chemical fertilizers, irrigation water, pesticides, and crop losses during harvest or at various stages throughout the production cycle. Accurately quantifying these losses allows for a more comprehensive understanding of the total costs and energy expenditures involved in sugar beet production. To quantify the losses, various formulas were applied, each designed to account for the specific nature of the inputs and their losses during the production process. These formulas relied on the coefficients presented in Table 2, which provide values for the losses of fertilizers, irrigation water, and pesticides to the environment, as well as crop losses during the harvesting process. These coefficients were derived from a combination of empirical data and established models, ensuring that the calculations were both accurate and aligned with industry standards.

One significant aspect of this study is the inclusion of fertilizer losses that are released into the environment through water, air, and soil. Fertilizers, particularly nitrogen-based fertilizers, can contribute to environmental pollution if not properly managed. Losses from chemical fertilizers can occur through various pathways, including leaching into water bodies, volatilization into the air as gases such as ammonia, and soil runoff. The study used standardized coefficients for these losses, helping to estimate the amount of fertilizer that does not contribute to crop growth but instead escapes into the environment. Another critical area of the study was the emissions from pesticides used in sugar beet farming. Pesticides, such as fungicides, insecticides, and herbicides, can have significant environmental impacts, including contamination of water and air. To estimate these emissions accurately, the study used the PestLCI 2.0 model, a widely recognized tool for calculating pesticide emissions. This model provides a modeled inventory list for the emissions of pesticides from the environment (ecosphere) to agricultural lands (techno-sphere). It helps to calculate the amount of pesticide emissions released to water and air, allowing the study to model their environmental impact in detail. The PestLCI 2.0 model offers a comprehensive framework for environmental impact modeling, as described by Renaud-Gentié et al. (2015). It accounts for the type of pesticide used and the specific environmental conditions of the region, making it a reliable tool for assessing the impact of pesticide use on the local ecosystem.

The application of nitrogen fertilizers—particularly in the form of urea—can result in significant energy losses due to chemical transformations that occur during their breakdown. The conversion of urea to ammonia (a process called ammonification) leads to the release of energy that was initially contained in the fertilizer. To accurately calculate the energy loss associated with this chemical transformation, the study utilized the concept of standard enthalpy of formation. The standard enthalpy of formation is a thermodynamic concept that helps quantify the energy stored in each chemical compound. By comparing the enthalpy of formation for urea and ammonia, the amount of energy released during the transformation process can be determined. This energy loss represents a significant cost, both economically and in terms of energy efficiency, as a portion of the applied fertilizer does not contribute to crop growth but is instead lost to the atmosphere. Table 2 provides the relevant values for the standard enthalpy of formation of urea and ammonia, allowing for precise calculation of the energy lost during the urea-to-ammonia conversion process. The energy lost in this transformation is a crucial factor to consider when calculating the total energy input required for sugar beet production. The emissions of nitrogen compounds such as ammonia and nitrate are significant contributors to both environmental pollution and energy loss in agricultural production. In this study, nitrogen emissions were calculated based on the total nitrogen consumed by the crops, as measured by fertilizer consumption. Using the conversion coefficients provided in Table 3, the amount of nitrogen released as ammonia to the air and nitrate to water was estimated.

Table 3. Coefficients used to calculate on-farm emissions for sugar beet production (IPCC, 2006)

Emissions and calculation formulas		Coefficients
Emissions from nitrogen fertilizers	$\frac{kg\ N_2O - N}{kg\ N_{in}}$	0.12 to air
	$\frac{kg\ NO_3^- - N}{kg\ N_{in}}$	0.3 to water
Emission conversion factor		
kg NH_3 – N to kg NH_3	$\frac{14}{17}$	
kg NO_3 – N to kg NO_3	$\frac{14}{62}$	
kg P_2O_5 to kg phosphorus	$\frac{62}{142}$	

These coefficients represent the ratio of nitrogen released to the total nitrogen consumed, based on established research and previous studies. In addition, the study also incorporated conversion coefficients for transforming nitrate into nitrogen oxide (NO_x). The release of nitrogen oxides into the atmosphere contributes to air pollution and is another form of energy loss that must be considered when evaluating the environmental and economic efficiency of the production process. The coefficients used in this study were derived from previous studies on nitrogen fertilizer emissions, ensuring that the estimates were accurate and reflective of local conditions. Table 3 presents the conversion coefficients and formulas used to calculate nitrogen fertilizer losses, offering a clear framework for estimating the emissions and energy losses associated with fertilizer use. By calculating the losses at each stage of the process, the study provides a detailed picture of the energy and material flows within the sugar beet production system.

2.1.9. Agricultural operations in sugar beet production in Khuzestan

The agricultural operations involved in the production of sugar beet crops in Khuzestan are summarized in Table 4. These operations are critical in shaping the efficiency of the production process, as they directly affect the use of inputs, energy consumption, and the overall yield of the crop. The specific timing and nature of these operations are tailored to the local climate and soil conditions, which play a key role in optimizing the growth of sugar beet. The production of sugar beet in Khuzestan follows a structured sequence of agricultural activities, with key operations taking place during specific months of the agricultural calendar. For example, primary tillage and seedbed preparation are typically carried out during August. These early operations are essential for creating the optimal soil structure and conditions for seed germination and root development.

Table 4. Agricultural operations for sugar beet production during the growing season

Agricultural operation	Period	Required equipment	Frequency
Pre-plant irrigation	August 11 - August 22		1
Primary tillage	August 11 - September 11	Moldboard plow and disc	2
Application of poultry manure	September 11 - September 16	Manure spreader	1
Secondary tillage	September 16 - September 23	Disc and leveler	1
Base fertilization	September 23 - October 2	Fertilizer spreader	1
Creating furrows and ridges	October 2 - October 7	Furrower	1
Pre-plant irrigation	October 7 - October 12		1
Planting	October 12 - October 31	Planter	1
Regular irrigation	From planting to harvest		
Weed control	2-3 weeks after planting and ongoing		
Side-dress fertilization	First stage: 4-6 weeks after planting; subsequent stages every 4-6 weeks	Fertilizer spreader	4
Manual or mechanical weeding	1-2 months after planting	Manual labor	1
Pest and disease control	Throughout the growing period	Sprayer	2
Thinning of seedlings	3-4 weeks after planting	Manual labor	1
Stopping irrigation before harvest	2-3 weeks before harvest		1
Harvest operations	Late April - Late June	Topper, chopper, other Harvesting machines	1

In addition to tillage and seedbed preparation, several other essential agricultural operations are carried out throughout the sugar beet planting season, as outlined in Table 4. These operations include tasks such as:

- Seed sowing: The planting of sugar beet seeds in the prepared beds, which typically occurs following the tillage operations.
- Irrigation: Given the climate of Khuzestan, irrigation is a key operation throughout the growth cycle of the sugar beet crop. Efficient irrigation techniques are essential for ensuring optimal water availability for crop growth while minimizing water wastage.
- Fertilizer application: The use of fertilizers, particularly nitrogen-based fertilizers, is a common practice to provide the essential nutrients for the crop. Fertilizer application schedules are typically aligned with the growth stages of sugar beet to ensure effective nutrient uptake.
- Pest and disease management: The application of pesticides and other pest control measures is essential to protect the crop from common pests and diseases. Pesticide application is generally timed to coincide with periods of high pest activity, which can vary based on local environmental factors.
- Harvesting: The final operation in the production cycle is harvesting, which takes place after the crop has matured. Harvesting is a labor-intensive operation that requires careful management to minimize crop loss and ensure maximum yield. Each of these operations has a direct impact on the material and energy flows within the system, contributing to the overall cost and energy efficiency of sugar beet production. The timing, frequency, and

intensity of these operations are crucial factors for optimizing both resource use and crop yield. By detailing these agricultural operations, Table 4 provides a comprehensive overview of the production process, which is essential for evaluating the costs, energy inputs, and environmental impacts of sugar beet production in Khuzestan. This information also aids in identifying areas where efficiencies can be improved, such as through better irrigation practices, optimized fertilizer use, or the adoption of more efficient machinery and harvesting techniques.

2.1.10. Cost coefficients for inputs and outputs

In order to comprehensively understand the cost structure of sugar beet production on farms, it is essential to convert both inputs and outputs into their respective cost equivalents. This conversion allows for a clear comparison of the economic performance of sugar beet production and enables identification of areas where cost optimization can be achieved. The main inputs considered in this analysis include: Fertilizers (both chemical and organic), Pesticides, Labor, Machinery (fuel, maintenance, etc.), and irrigation water. These inputs were valued based on their market prices during the study period. Similarly, the outputs of sugar beet production were assigned a dollar value, using the guaranteed price for sugar beets with a 16% sugar content, which was the standard price during the year of the study. This price reflects the price that farmers receive for their sugar beet harvest and serves as a basis for evaluating the profitability of the crop. To gain a deeper understanding of the economic performance of sugar beet production, several economic indicators were calculated. These indicators provide insight into the profitability, efficiency, and sustainability of the production process. The key economic indicators used in this study include: Total Value of Production (TVP): This represents the total dollar value of all sugar beets produced, based on the guaranteed price for beets with a 16% sugar content. It provides a comprehensive overview of the revenue generated from the harvest. Gross Return (GR): The gross return represents the total revenue from sugar beet production before subtracting costs. This value gives an indication of the potential earnings from the crop, providing an initial benchmark for evaluating profitability. Benefit-to-Cost Ratio (BCR): The BCR is one of the most widely used indicators of profitability in agricultural production. It is calculated by dividing the total revenue (or gross return) by the total production costs. A BCR greater than 1 indicates that the revenue exceeds the costs, signaling a profitable operation. In contrast, a BCR of less than 1 suggests that the operation is not economically sustainable without intervention. Economic Productivity (EP): This indicator measures the economic efficiency of sugar beet production by comparing the value of the output (i.e., the dollar value of the produced sugar beets) to the inputs used in the production process. A higher EP indicates more efficient use of resources, as it reflects higher revenue relative to the inputs. These economic indicators provide a well-rounded understanding of the economic sustainability of sugar beet production. They offer valuable insights for farmers, policymakers, and researchers looking to optimize the production process and improve profitability. The calculated economic indicators, along with the detailed breakdown of input and output costs, are presented in Table 5. This table provides a clear snapshot of the financial viability of sugar beet production in the region, offering both the overall gross return and the specific costs associated with each input. By comparing these values, it becomes possible to identify cost-effective practices and areas where improvements could enhance economic productivity.

Table 5. Economic indicators of sugar beet production in Khuzestan

Economic indicators	Unit	Equation
Total value of production	$\$ ha^{-1}$	GVP =Y (kg ha^{-1}) × P ($\$ ha^{-1}$)
Gross return	$\$ ha^{-1}$	GR=GVP ($\$ ha^{-1}$)-Variable costs ($\$ ha^{-1}$)
Benefit to cost ratio		CBR=GVP ($\$ ha^{-1}$) / TC ($\$ ha^{-1}$)
Economic productivity	kg $\$^{-1}$	EP=Y(kg) / Variable costs ($)

* In the table, Y represents the sugar beet yield (kg ha^{-1}), P is the price of sugar beet ($\$ kg^{-1}$), VC denotes variable costs ($\$ ha^{-1}$), and TC stands for total production costs ($\$ ha^{-1}$).

2.1.11. Energy coefficients for inputs and outputs

In line with the ISO 14051 standards, a comprehensive assessment of the energy flow within the sugar beet production system requires the conversion of all inputs and outputs—whether positive products or negative by-products—into their respective energy equivalents. This conversion process allows for a more detailed understanding of the energy dynamics within the production system and is crucial for identifying areas where energy use can be optimized, ultimately leading to more sustainable agricultural practices. For this study, a range of inputs commonly used in sugar beet production were analyzed in terms of their energy content. For each of these inputs, the study used energy coefficients—standardized values that represent the amount of energy embedded in the input. These coefficients were derived from various sources, including literature and databases, to ensure that the energy equivalents for each input were accurate and reflective of real-world conditions. Once the energy equivalents for each input were determined, a set of energy indicators was calculated to evaluate the efficiency of the energy use in sugar beet production. These indicators help to quantify how much energy is used relative to the output produced, providing a clear picture of the overall energy performance of the agricultural system.

The following key energy indicators were calculated in this study: Energy Productivity (EP): This indicator measures the amount of output (in terms of the energy equivalent of the sugar beets produced) relative to the energy input used in the system. Higher energy productivity indicates that the system is able to produce more output with less energy input, a key aspect of sustainability in agricultural production. Energy Use Efficiency (EUE): Energy use efficiency is calculated as the ratio of useful energy output (in this case, the energy equivalent of the sugar beets produced) to the total energy input. A higher EUE suggests that energy is being utilized effectively in the production process, minimizing waste and inefficiencies. Net Energy (NE): Net energy represents the total energy output of the system minus the total energy input. A positive net energy value indicates that the production system generates more energy than it consumes, a desirable outcome for ensuring the long-term sustainability of the farming practice. Specific Energy (SE): Specific energy is the amount of energy required to produce a unit of output, typically expressed as energy per kilogram or per ton of sugar beets produced. Lower specific energy values indicate that less energy is needed to produce each unit of output, suggesting greater efficiency in the production process. The calculated energy coefficients and energy indicators for sugar beet production are summarized in Table 6. This table provides a clear overview of the energy flows within the system, showing the total energy inputs, the energy outputs, and the various energy indicators that assess the system's efficiency. By analyzing these data, it is possible to pinpoint areas where energy consumption can be reduced, such as through improved irrigation practices, better fertilizer management, or the use of more efficient machinery.

Table 6. Energy Indicators of sugar beet production in Khozestan

Energy indicators	Unit	Equation
Energy productivity	kg MJ^{-1}	$EP = \frac{Y\ (kg\ ha^{-1})}{IE\ (MJ\ ha^{-1})}$
Energy use efficiency		$EUE\ (ER) = \frac{OE\ (MJ\ ha^{-1})}{IE\ (MJ\ ha^{-1})}$
Net energy	MJ ha^{-1}	$NE = OE\ (MJ\ ha^{-1}) - IE\ (MJ\ ha^{-1})$
Specific energy	MJ kg^{-1}	$SE = \frac{IE\ (MJ\ ha^{-1})}{Y\ (kg\ ha^{-1})}$

* In the IE equations, IE represents input energy in MJ ha^{-1}, OE represents output energy in MJ ha^{-1}, and Y is the sugar beet yield ha^{-1}.

3. Results and discussion

3.1. Energy assessment

Table 7 presents the energy consumption per unit of inputs and outputs for sugar beet production in Khuzestan, providing minimum, average, and maximum values for energy use across different stages of production. These figures offer valuable insights into the energy intensity of the sugar beet farming system, which is crucial for improving energy efficiency and enhancing the sustainability of agricultural practices.

The study found a wide range of energy inputs across different sugar beet fields, with values for energy consumption per hectare ranging from a minimum of 23,745 MJ ha^{-1} to a maximum of 77,170 MJ ha^{-1}. The average energy consumption was 52,410 MJ ha^{-1}, which represents the typical energy input in sugar beet farming in Khuzestan during the study period. Labor Energy Consumption: The energy used for human labor varied significantly across fields with different yield levels. For fields with the lowest, highest, and average yields, the energy used for labor was 942.8 MJ ha^{-1}, 1,975.7 MJ ha^{-1}, and 1,459.2 MJ ha^{-1}, respectively. This energy is associated with key agricultural operations, including bed preparation, irrigation, fertilization, weeding, pest control, topping, harvesting, and transportation. Among these operations, weeding and thinning were found to consume the most labor, highlighting areas where efficiency improvements could reduce labor-related energy consumption.

Table 7. Energy input and output flow in sugar beet production systems in Khuzestan

Input-output flow	Mean	Min	Max	Energy equivalent (MJ unit^{-1})	Mean	Min	Max
Human labor	744.5	481.0	1008.0	1.96	1459.2	942.8	1975.7
Agricultural machinery	61.0	54.0	66.0	62.7	3824.7	3385.8	4138.2
Nitrogen	382.7	50.0	650.0	66.14	25311.1	3307.0	42991.0
Phosphate	124.4	50.0	250.0	12.44	1547.5	622.0	3110.0
Potassium	117.3	0.0	250.0	11.15	1307.9	0.0	2787.5
Poultry manure	1188.0	0.0	2000.0	0.3	356.4	0.0	600.0
Pesticides	4.5	2.0	6.0	199	895.5	398.0	1194.0
Herbicide	3.9	0.0	8.0	238	928.2	0.0	1904.0
Fungicides	5.0	0.0	10.0	92	460.0	0.0	920.0
Irrigation water	8000.0	8000.0	8000.0	1.02	8160.0	8160.0	8160.0
Diesel fuel	144.5	122.6	166.3	56.31	8135.7	6905.9	9365.5
Seed	2.0	2.0	2.0	11.93	23.9	23.9	23.9
Yield	74000.0	48000.0	110000.0	16.8	1243200.0	806400.0	1848000.0
NH_3 by chemical fertilizers to air	124.8	16.3	212.0	2.7	336.9	44.0	572.3
N_2O to air	4.8	0.6	8.1	2.9	13.9	1.8	23.6
Nitrate to water	9.6	1.3	16.3	12.44	119.0	15.6	202.2
Phosphate to water	3.0	2.4	3.8	3.32	10.0	7.9	12.6
Emissions by biocides to air	2.0	0.0	4.0	132.5	258.4	0.0	530.0
Emissions by biocides to water	2.5	0.0	5.0	132.5	331.3	0.0	662.5
Emissions by biocides to soil	2.5	0.0	5.0	132.5	331.3	0.0	662.5
Yield loss	6000	3892	8919	16.8	100800.0	65383.8	149837.8

Machinery Energy Consumption: The energy consumption from agricultural machinery ranged from 3,385 MJ ha^{-1} to 4,138 MJ ha^{-1}. This variation is largely due to differences in machinery usage, including tractors for field preparation and harvesters. The largest share of energy input in the agricultural systems was attributed to nitrogen fertilizers, irrigation water, and diesel fuel. In low-yield systems, the energy contribution from nitrogen fertilizers was lower than that from irrigation water and diesel fuel. In high-yield systems, nitrogen fertilizer accounted for the largest share of energy input, reaching 55%. The average consumption of nitrogen fertilizer in these fields was 650 kg ha^{-1}. The results of this study on energy consumption in sugar beet production are consistent with findings from previous research. Farid et al. (2013) found that the highest energy consumption in sugar beet production was attributed to chemical fertilizers, electricity, and diesel fuel, accounting for 38.46%, 29.58%, and 13.55%, respectively. Similarly, Firouzi et al. (2022) findings indicated that the total energy consumption for sugar beet and sugarcane production was 58,487.80 MJ ha^{-1} and 61,220.62 MJ ha^{-1}, respectively. The largest share of energy expenditure was allocated to chemical fertilizers (35.47% for sugarcane), electricity (23.62% for sugar beet), and water (22.45% for sugar beet). Notably, 77.39% of the total energy consumption for sugar beet and 83.69% for sugarcane were derived from non-renewable energy sources. According to Asgharipour et al. (2012), the total energy input was 42,231.9 MJ ha^{-1}, with around 29% of this energy coming from chemical fertilizers and 22% from irrigation water. The consistent results across these studies highlight that despite varying geographical locations and methodologies, nitrogen fertilizers, diesel fuel, and irrigation water remain the dominant energy-consuming factors in sugar beet production. These studies underscore the critical role of improving fertilizer management, optimizing irrigation practices, and utilizing more energy-efficient machinery in reducing energy consumption and enhancing the sustainability of sugar beet farming. The study also considered the energy output from sugar beet production, which is a key factor in assessing the energy efficiency of the farming system. The minimum, maximum, and average yields observed were 48 t ha^{-1}, 110 t ha^{-1}, and 74 t ha^{-1}, respectively. These yield values reflect the varying levels of crop productivity across the region and highlight the relationship between energy inputs and yields. Energy inputs were further categorized into:

- Direct Energy: This includes labor, diesel fuel, and seed energy.
- Indirect Energy: This includes machinery, chemical fertilizers, poultry manure, and pesticides.
- Renewable Energy: This is primarily human labor, poultry manure, and seed.
- Non-renewable Energy: This includes machinery, chemical fertilizers, diesel fuel, and pesticides.

The results showed that 97% of the energy in sugar beet production came from non-renewable sources, while only 3% was derived from renewable energy. In terms of energy categories, 34% of the total energy input was direct energy, and 66% was indirect energy. The energy input analysis conducted using Material Flow Cost Accounting (MFCA) yielded similar results to conventional accounting methods, with the primary difference lying in the calculation of energy outputs and the associated energy indicators. One of the key findings of this study was the significant energy losses occurring during the harvest phase. The largest share of negative energy loss was associated with sugar beet loss during harvesting, accounting for more than 99% of the total negative energy. The maximum, minimum, and average losses of sugar beet during harvesting were 149,837 MJ ha^{-1}, 65,383 MJ ha^{-1}, and 100,800 MJ ha^{-1}, respectively. This negative energy loss was found to be 1.9 times the energy input on average.

In systems with low energy input consumption, the energy loss was 2.75 times higher than the energy input, while in systems with high energy input consumption, the loss was 1.94 times higher. This highlights the inefficiencies in the harvesting process and suggests that improving harvesting techniques and reducing crop loss during this phase could significantly reduce overall energy losses in sugar beet production (Fig. 4).

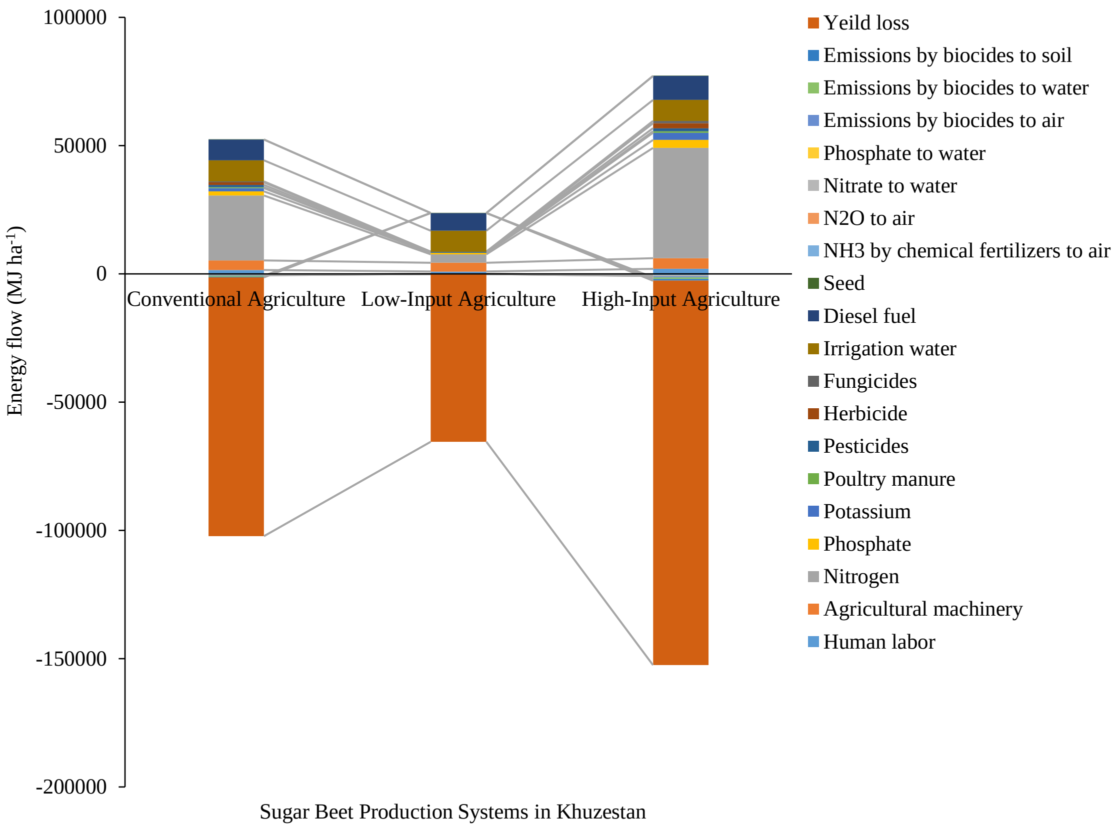

Figure 4. Energy flow of inputs and outputs in sugar beet production systems

The energy ratio, which measures the output energy relative to the total input energy, was found to be 23.72 in conventional accounting and 21.77 in material flow cost accounting (MFCA). The difference of 2 units in the energy ratio can be attributed to the negative energy losses, which amounted to 102,201 MJ ha^{-1}. This discrepancy highlights the impact of energy losses, particularly from crop loss during the harvesting phase, on the overall energy efficiency of the system. While conventional accounting does not incorporate these losses, MFCA accounts for them, leading to a more comprehensive understanding of energy flow in the production process.

In terms of energy efficiency, there was no significant difference between conventional accounting and MFCA. This is because negative energy losses are not considered in the calculation of energy efficiency in either method. Therefore, both accounting methods yielded the same energy efficiency value of 1.41, reflecting the total energy output relative to the total energy input, excluding losses. The specific energy, which examines the energy input per unit of crop yield, was calculated to be 0.71. This indicates the amount of energy required to produce one kilogram of sugar beet, highlighting the energy intensity of the production process. Lastly, the net energy—which represents the difference between the total energy output and total energy input—showed a 102,201 MJ ha^{-1} difference between conventional accounting and MFCA. This difference further underscores the importance of considering energy losses in the production system for a more accurate assessment of net energy and overall energy efficiency (Table 8). In summary, while the energy efficiency and specific energy calculations remain the same across both accounting methods, the energy ratio and net energy are significantly impacted by the consideration of negative energy losses in MFCA, providing a more detailed and realistic picture of the energy dynamics in sugar beet production.

Table 8. Energy indicators for sugar beet production

	Unit	Equation	MFCA			CA		
			Mean	Min	Max	Mean	Min	Max
A. Energy forms								
Direct energy	MJ	Human labor + Diesel fuel + Seed	9618.749	7872.478	11365.02	9618.749	7872.478	11365.02
Indirect energy	MJ	Machinery + Chemical fertilizers + Poultry manure+ Biocides	34631.35	7712.8	57644.7	34631.35	7712.8	57644.7
Renewable energy	MJ	Human labor + Poultry manure + Seed	1815.62	942.76	2575.68	1815.62	942.76	2575.68
Non-renewable energy	MJ	Machinery + Chemical fertilizers + Diesel fuel + Biocides	54419.18	26188.32	78732.24	54419.18	26188.32	78732.24
B. Energy flow								
Input energy	MJ		52410.1	23745.28	77169.72	52410.1	23745.28	77169.72
Output energy	MJ		1140999	740946.9	1695497	1243200	806400	1848000
Positive energy	MJ		1243200	806400	1848000	1243200	806400	1848000
Negative energy	MJ		102200.7	65453.1	152503.4	0	0	0
C. Energy indices								
Energy ratio		Output energy (MJ ha^{-1}) / Total input energy (MJ ha^{-1})	21.7706	31.20397	21.97101	23.72062	33.96044	23.94722
Energy productivity	kg MJ^{-1}	Crop yield (kg ha^{-1}) / Total input energy (MJ ha^{-1})	1.411942	2.021455	1.42543	1.411942	2.021455	1.42543
Specific energy	MJ kg^{-1}	Total input energy (MJ ha^{-1}) / Crop yield (kg ha^{-1})	0.708245	0.494693	0.701543	0.708245	0.494693	0.701543
Net energy	MJ	Output energy (MJ ha^{-1}) / Total input energy (MJ ha^{-1})	1088589	717201.6	1618327	1190790	782654.7	1770830

3.2. Economic evaluation

The cost equivalents of inputs and outputs for sugar beet production under the conditions of Khuzestan are presented in Table 9 and Fig. 5. The economic evaluation of sugar beet production in Khuzestan, as presented in Table 9, reflects the cost equivalents of inputs and outputs under local conditions. The study found a significant variation in the economic performance of sugar beet farms, with the highest economic value produced being \$6600 ha^{-1} and the lowest at \$2880 ha^{-1}. The average economic performance was calculated to be \$4440 ha^{-1}, indicating the typical revenue generated ha^{-1} from sugar beet production. On average, the total production cost for sugar beet was \$1192 ha $^{-1}$, with a maximum of \$1649 and a minimum of \$739 ha^{-1}.

The highest share of production costs was attributed to labor, which accounted for a significant portion of total costs. The labor cost in sugar beet production ranged from \$481 to \$1008 ha^{-1}, with an average of \$744 ha^{-1}. This highlights the labor-intensive nature of sugar beet farming in the region. Topping and weeding were identified as the operations requiring the most labor input. Labor costs constituted 61% to 65% of the total production costs, with an average of 63%. This significant share of labor costs emphasizes the need for more efficient labor management practices and the potential for automation or mechanization in sugar beet production to reduce overall costs.

The use of chemical fertilizers (including nitrogen, potassium, and phosphorus) accounted for an average of 12% of the total production costs, with a range from 3% to 17%. Pesticides made up 5% of the production costs, ranging from 1% to 6%. These figures highlight the importance of efficient fertilizer and pesticide use in minimizing production costs while maintaining crop yields. The study also examined the negative economic losses associated with sugar beet production. The largest contributor to economic losses was beet loss during harvest, which accounted for 71% of the total economic loss, amounting to an average loss of $360 ha^{-1} (with a maximum of $535 and a minimum of $233 ha^{-1}). This loss represents a significant inefficiency in the harvest process, underlining the need for improvements in harvesting techniques to reduce these losses. Irrigation water losses were the second-largest contributor to economic losses, representing 19% of the total losses, with an average economic value of $96 ha^{-1} (ranging from $67 to $133 ha^{-1}).

Irrigation inefficiencies are a critical issue in Khuzestan, where water resources are often limited, and improving irrigation efficiency could help reduce these losses. The total economic value of negative losses across the sugar beet production systems was $507 ha^{-1} on average, ranging from $332 to $727 ha^{-1}. These losses represented approximately 42% of the total input costs, with low-input systems experiencing losses equivalent to 45% of input costs, and high-input systems showing losses of 44%. These findings highlight the economic inefficiency resulting from crop losses during harvest and inefficiencies in water management, both of which are areas that can be targeted for improvement.

The gross production value of sugar beet, calculated using material-energy flow costing (MEFC), averaged $4651 ha^{-1}, with a minimum of $3020 ha^{-1} and a maximum of $6887 ha^{-1}. This value represents the total revenue generated from sugar beet production, considering both direct and indirect economic flows. For every dollar invested in sugar beet farming, the average farmer in Khuzestan earned $3.8, with low-input systems achieving $4.09 and high-input systems reaching $4.17 per dollar invested. This benefit-to-cost ratio indicates that sugar beet farming in Khuzestan is generally economically viable, but there are variations based on input usage. The net income for sugar beet farmers averaged $3458 ha^{-1}, with net income ranging from $2281 to $5237 ha^{-1}, reflecting differences in yield, input costs, and production efficiency. The economic efficiency of sugar beet production was calculated to be 62 kg $\$^{-1}$ spent on production. This means that for every dollar invested, an average of 62 kg of sugar beet is produced. Low-input farms, which had higher economic efficiency of 64.9 kg $\$^{-1}$, experienced lower yields, which affected their overall economic performance despite the higher efficiency per dollar spent. This suggests that while low-input systems may be more energy- and cost-efficient per unit of output, they may not always produce sufficient yields to generate higher overall profits. On the other hand, high-input systems with lower economic efficiency per dollar invested tended to achieve higher yields, resulting in higher gross production values and net income.

Table 9. Economic input and output flow in sugar beet production systems in Khuzestan

Input-output flow	Unit	Mean	Min	Max	Price ($ unit^{-1})	Mean	Min
Human labor	744.5	481.0	1008.0	1	744.50	481.00	1008.00
Agricultural machinery	61.0	54.0	66.0	1.2	73.20	64.80	79.20
Nitrogen	382.7	50.0	650.0	0.14	53.58	7.00	91.00
Phosphate	124.4	50.0	250.0	0.3	37.32	15.00	75.00
Potassium	117.3	0.0	250.0	0.43	50.44	0.00	107.50
Poultry manure	1188.0	0.0	2000.0	0.01	11.88	0.00	20.00
Pesticides	4.5	2.0	6.0	4.4	19.80	8.80	26.40
Herbicide	3.9	0.0	8.0	4.4	17.16	0.00	35.20
Fungicides	5.0	0.0	10.0	4.4	22.00	0.00	44.00
Irrigation water	8000.0	8000.0	8000.0	0.02	160.00	160.00	160.00
Diesel fuel	144.5	122.6	166.3	0.02	2.89	2.45	3.33
Seed	2.0	2.0	2.0	0.01	0.02	0.02	0.02
Yield	74000.0	48000.0	110000.0	0.06	4440.00	2880.00	6600.00
Positive output							
Irrigation water loss	4800.0	4800.0	4800.0	0.02	96.00	96.00	96.00
NH_3 by chemical fertilizers to air	124.8	16.3	212.0	0.14	17.47	2.28	29.67
N_2O to air	4.8	0.6	8.1	0.14	0.67	0.09	1.14
Nitrate to water	9.6	1.3	16.3	0.14	1.34	0.18	2.28
Phosphate to water	3.0	2.4	3.8	0.3	0.90	0.72	1.14
Emissions by pesticide	2.0	0.0	4.0	4.4	8.58	0.00	17.60
Emissions by herbicide	2.5	0.0	5.0	4.4	11.00	0.00	22.00
Emissions by fungicide	2.5	0.0	5.0	4.4	11.00	0.00	22.00
Yield loss	6000	3892	8919	0.06	360.00	233.51	535.14

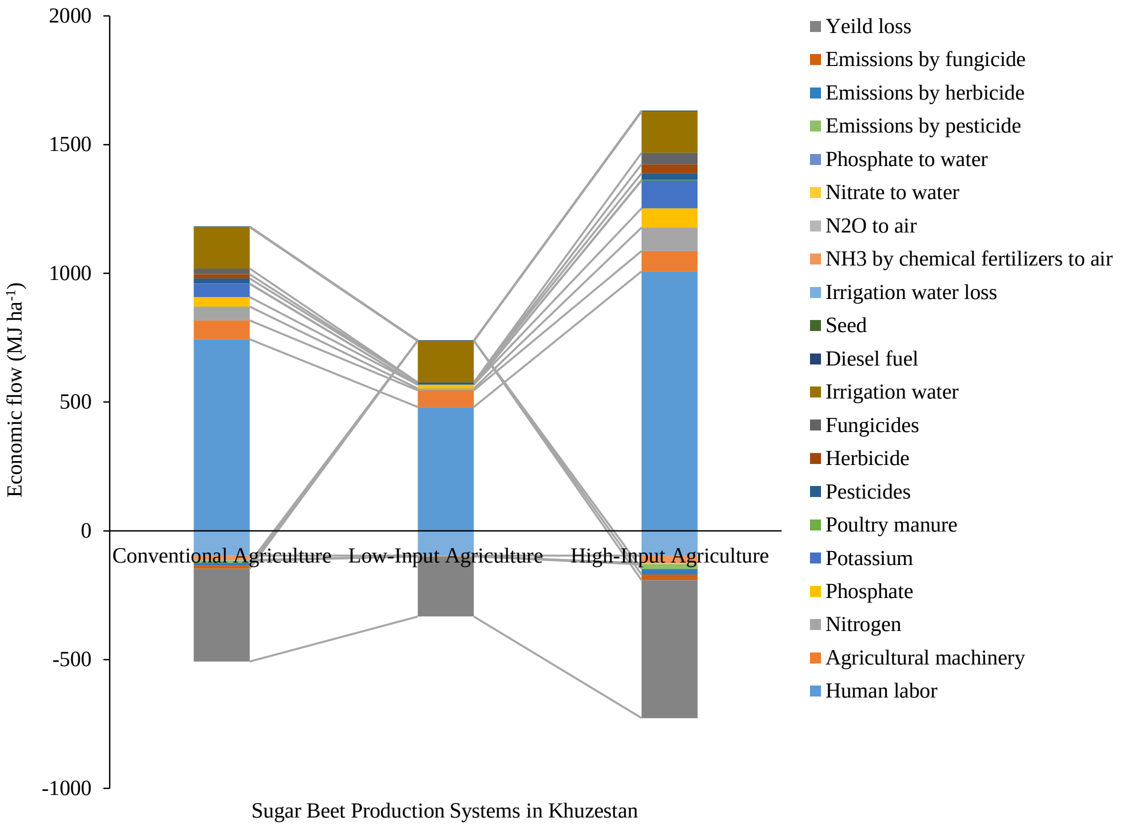

Figure 5. Economic flow of inputs and outputs in sugar beet production systems

4. Conclusion

This study provides the first comprehensive analysis of the economic and energy dynamics of sugar beet production in Khuzestan, applying the Material and Energy Flow Cost Accounting (MEFCA) methodology. This innovative approach enabled a more precise evaluation of both economic and energy indices by considering both positive and negative outputs—an aspect often overlooked in conventional accounting frameworks. By factoring in inefficiencies and waste, this method offers a more holistic assessment of energy utilization and economic performance, thereby identifying critical areas for improvement in energy efficiency and farm profitability.

The results highlight that the primary driver of energy consumption in sugar beet production in Khuzestan is the use of chemical fertilizers, especially nitrogen fertilizers. These inputs represent a substantial proportion of total energy expenditure, reflecting the system's heavy reliance on high-energy materials. Following fertilizers, fuel and irrigation water also emerge as significant contributors to the overall energy use. The total energy consumption per hectare for sugar beet production in Khuzestan was found to be 52,410 MJ, of which 1,815 MJ is sourced from renewable energy and 50,549 MJ from non-renewable energy. The stark disparity between the two underscores the unsustainable nature of the current energy profile and points to an urgent need for transition toward more sustainable energy practices. To enhance the sustainability of the production system, a strategic shift towards reducing dependence on non-renewable energy and increasing renewable energy utilization is essential. This transition will be pivotal in improving both the environmental and economic sustainability of sugar beet production in Khuzestan.

Economically, the study demonstrates that sugar beet production remains viable under current market conditions, primarily due to subsidies on energy carriers that obscure the true cost of inputs. However, when accounting for the real price of energy inputs—excluding subsidies—the economic viability of the system becomes less favorable. This highlights the need for more stringent energy management practices to maintain long-term profitability. Efficient energy use, through both consumption reduction and input cost optimization, will be crucial for ensuring the financial sustainability of sugar beet production in the region. While current systems are economically profitable, significant opportunities exist to further enhance profitability through process optimization. Minimizing harvest losses, particularly through advancements in mechanized harvesting techniques, improved topping processes, and the adoption of modern irrigation technologies, could lead to substantial gains. These improvements not only have the potential to reduce energy consumption but also enhance crop yields, translating to increased economic returns for farmers.

In conclusion, while sugar beet production in Khuzestan is economically viable in the short term, its long-term sustainability—both in terms of energy use and financial profitability—necessitates significant adjustments. Shifting to renewable energy sources, improving energy efficiency, and embracing modern farming technologies are essential steps to ensure that the sector remains resilient in the face of escalating energy costs and growing environmental concerns. The insights from this study provide valuable guidance for policymakers, agricultural planners, and farmers, offering actionable strategies for enhancing both the economic and environmental sustainability of sugar beet production in Khuzestan.

Suggestions for improvement:

- Energy Use Optimization: Prioritize the adoption of renewable energy sources such as solar or wind power to replace non-renewable energy inputs. This could help offset the reliance on fossil fuels and mitigate the environmental impact of energy consumption.
- Advanced Irrigation Techniques: Transition to modern, water-efficient irrigation systems (e.g., drip irrigation) that would minimize water waste, reduce energy consumption, and improve crop yield.
- Technology Integration in Harvesting: Invest in advanced harvesting machinery to reduce crop loss during harvest, which would not only improve energy efficiency but also boost yield and overall farm profitability.
- Policy Recommendations: Policymakers should consider reducing subsidies on non-renewable energy sources and redirecting funds towards incentivizing the adoption of sustainable agricultural practices, renewable energy, and energy-efficient technologies.
- Long-Term Profitability Models: Future studies should consider integrating economic forecasting models that account for changing energy prices and environmental policies to better predict the long-term viability of the sugar beet production system.

By incorporating these suggestions, sugar beet production in Khuzestan could become both more sustainable and more economically resilient in the future.

Conflict of interests

All authors declare no conflict of interest.

Ethics approval and consent to participate

No humans or animals were used in the present research. The authors have adhered to ethical standards, including avoiding plagiarism, data fabrication, and double publication.

Consent for publications

All authors read and approved the final manuscript for publication.

Availability of data and material

All the data are embedded in the manuscript.

Authors' contributions

All authors had an equal role in study design, work, statistical analysis and manuscript writing.

Informed consent

The authors declare not to use any patients in this research.

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