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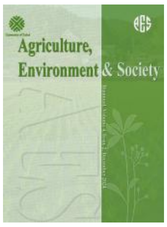

A material flow cost accounting (MFCA) approach to sustainable crop management: Case study of watermelon, onion, tomato, and wheat cultivation in Sistan and Baluchestan, Iran

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ABSTRACT

This study applied Material Flow Cost Accounting (MFCA) to assess the economic and environmental performance of four key crops—watermelon, onion, tomato, and wheat in the arid Sistan and Baluchestan Province of Iran. Using official 2022–2023 data aligned with ISO 14051, the research quantified input-output flows per hectare, including water, fertilizers, pesticides, energy, and labor, alongside outputs such as yield, emissions, and losses. Results revealed distinct trade-offs: onion achieved the highest economic returns (gross value: \$7352.7 ha^{-1}; benefit-cost ratio: 12.6) but incurred significant environmental costs, including nitrate leaching (57.6 kg ha^{-1}) and ammonia emissions (51.7 kg ha^{-1}). Tomato showed moderate profitability (\$5337.6 ha^{-1}) with poor energy efficiency (net energy: –30,622.44 MJ ha^{-1}), while watermelon offered balanced sustainability (economic productivity: 100.1 kg $\$^{-1}$; energy ratio: 0.84). Wheat, though economically limited (\$681.6 ha^{-1}), had the lowest environmental impact. The analysis highlighted that high-value crops (onion, tomato) generated substantial material losses and energy deficits, whereas low-input crops (watermelon, wheat) exhibited better resource efficiency. Key findings support optimized input management for high-value crops, promotion of watermelon in resource-limited systems, and integration of energy-environmental indicators in agricultural planning, establishing MFCA as an effective tool for sustainability assessment in dryland farming.

Highlights

- Employed material flow cost accounting to quantify hidden input inefficiencies and environmental costs.
- Onion delivered the highest financial returns but also the greatest material losses and emissions.
- Tomato recorded the lowest energy efficiency ratio, resulting in the largest net energy deficit.
- Wheat achieved the only positive net energy output coupled with superior energy productivity.
- Watermelon maintained moderate profitability and an energy ratio close to one, reflecting efficient resource use.

1. Introduction

Agriculture in arid and semi-arid regions plays a pivotal role in ensuring food security, sustaining rural livelihoods, and supporting local economies (Qader et al., 2021; Ravisankar et al., 2022). In Iran, one of the most challenging provinces in this regard is Sistan and Baluchestan, located in the southeast of the country. The province is characterized by extreme climatic conditions including high temperatures, low and erratic rainfall (less than 100 mm annually in many parts), intense evapotranspiration, frequent sandstorms, and recurrent droughts (Afrakhteh, 2006; Fanni et al., 2014). These conditions make agriculture both a necessity and a formidable endeavor. Despite these challenges, the region continues to cultivate a range of crops that are critical for both local food consumption and commercial distribution. Among the most widely grown crops in the province are watermelon (*Citrullus lanatus*), onion (*Allium cepa*), tomato (*Solanum lycopersicum*), and wheat (*Triticum aestivum*). Each of these crops plays a unique role in the regional food system. Watermelon and tomato are high-yielding, short-cycle crops with significant market demand,

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both within and outside the region (Van Beek et al., 2008). Onion is a staple in Iranian diets and has high storage potential, making it suitable for local consumption and inter-provincial trade. Wheat remains the cornerstone of food security, as bread is the most consumed food item across Iranian households. Despite their agronomic and economic importance, the sustainability of cultivating these crops in Sistan and Baluchestan is increasingly under scrutiny due to escalating environmental pressures and resource constraints (Ghafarimoghadam et al., 2021). The reliance on water-intensive farming methods in a water-scarce region has led to critical groundwater depletion and soil salinization in several areas of the province. Moreover, excessive and often inefficient use of fertilizers and pesticides has raised concerns regarding water pollution, greenhouse gas emissions, and long-term soil degradation. In addition to environmental challenges, economic inefficiencies in input use particularly labor, fertilizers, irrigation, and energy are limiting profitability for smallholder farmers. These issues are further compounded by poor market infrastructure, limited access to post-harvest storage, and lack of timely agricultural extension services (Mirshekari et al., 2023; Golshani et al., 2023). Against this backdrop, there is a pressing need for a robust, integrated framework that can assess agricultural systems not only from a productivity standpoint but also in terms of economic efficiency and environmental sustainability. Such a framework should be able to identify input-output imbalances, quantify material losses, and suggest actionable interventions to optimize farming practices. While traditional accounting systems used in agriculture focus on direct financial costs and returns, they often fail to capture hidden inefficiencies and externalities, especially those related to environmental degradation and material waste (YarAhmadi et al., 2025).

Material flow cost accounting (MFCA) offers a promising solution to this gap. Developed initially as part of environmental management systems and formalized under the ISO 14051 standard, MFCA is a tool that maps the flow of materials and energy within production systems, distinguishing between positive products (saleable outputs) and negative products (waste, emissions, and losses) (Sahu et al., 2021). Unlike conventional cost accounting, MFCA assigns financial values to negative outputs, thereby revealing the cost implications of inefficiencies and environmental impacts (Dekamin et al., 2025a). This method allows producers to understand where resources are being lost and how such losses are affecting both their bottom line and the environment (Dekamin et al., 2024a).MFCA has been successfully applied to a variety of agricultural systems worldwide, including grape (Dekamin et al., 2024b), maize (Afshar and Dekamin, 2022), canola (Dekamin, 2021), sugar beet (YarAhmadi et al., 2025), and horticultural crops (Dekamin, 2024). In Iran, recent research has demonstrated the utility of MFCA in evaluating greenhouse systems (Dekamin et al., 2024a), medicinal plant production, and orchard crops (Dekamin et al., 2024b). However, its application in open-field row crops under arid conditions particularly in marginalized and climatically stressed regions like Sistan and Baluchestan remains limited.

The four crops selected for this study each present distinct input profiles and environmental interactions. Watermelon, with its sprawling growth and heavy fruit load, requires substantial amounts of water and nutrient inputs, making it prone to high material losses, particularly under flood irrigation methods commonly practiced in the region. Tomato, while less water-intensive than watermelon, is highly sensitive to pests and diseases, resulting in heavy reliance on chemical pesticides and fungicides. It also experiences substantial post-harvest losses due to its perishability and inadequate cold-chain infrastructure. Onion, though more resilient, involves significant manual labor during planting and harvesting stages, and may suffer from inefficient fertilization regimes. Wheat, as a relatively low-input crop, has more modest economic returns but is crucial for food sovereignty and social stability (Caldinhas et al., 2023). Evaluating these crops through the MFCA lens provides a unique opportunity to compare their economic productivity (e.g., gross value of production, net return, benefit-to-cost ratio) alongside environmental performance (e.g., emissions, nutrient leaching, yield loss). This dual-perspective assessment helps answer critical policy questions such as: Which crops are more resource-efficient under arid conditions? How can farmers reduce input losses and improve profitability without compromising environmental integrity? And what crop-specific interventions could help transition toward more sustainable farming systems in the region? In the context of climate-smart agriculture, MFCA provides a valuable decision-support mechanism that aligns well with broader environmental policy goals. Iran's agricultural strategy, as outlined in national development plans and climate adaptation policies, increasingly emphasizes reduced water consumption, improved input-use efficiency, and carbon footprint mitigation (Hashemi et al., 2017). MFCA not only aligns with these goals but provides a practical, farm-level accounting framework that can be implemented with basic data collection and analysis, making it suitable even for low-capacity rural settings (YarAhmadi et al., 2025).

This study, therefore, aims to fill a critical knowledge gap by applying MFCA to the comparative evaluation of watermelon, onion, tomato, and wheat production systems in Sistan and Baluchestan Province. By integrating environmental and economic indicators into a single evaluative framework, the research seeks to generate actionable insights that can guide farmers and policymakers in selecting and managing crops more sustainably. While MFCA has been applied to various agricultural systems globally, its use for open-field crops in arid regions like Sistan and Baluchestan remains limited. This study addresses this gap by (1) quantifying material/energy flows and losses for four key crops, (2) integrating environmental costs into economic assessments, and (3) providing comparative recommendations for sustainable crop selection. Our work advances MFCA’s applicability in resource-scarce contexts and supports Iran's national goals of water-use efficiency and emission reduction. Through this study, we hope to demonstrate how MFCA can serve not merely as an analytical tool, but as a transformative approach to rethinking agricultural production systems in fragile environments, thereby contributing to long-term food security, rural resilience, and environmental protection in one of Iran's most vulnerable provinces.

2. Materials and Methods

This study was conducted to assess and compare the economic and environmental performance of four major agricultural crops watermelon, onion, tomato, and wheat in the context of Sistan and Baluchestan Province, Iran, using the MFCA methodology. The province, with its arid and semi-arid climate, represents one of the most challenging yet critical agricultural regions in the country. Given the scarcity of water, high evapotranspiration, and limited infrastructure for input management and output distribution, optimizing agricultural production in this region requires careful analysis of both material flows and cost structures.

Unlike many empirical field studies that rely on direct sampling and primary data collection, this research is grounded in the use of secondary data obtained from the official database of the Ministry of Agriculture Jihad of Iran (2022-2023) (Maj, 2025). These data include information on crop-specific input consumption (e.g., fertilizers, water, biocides, labor), energy use, yield levels, and agricultural practices typical of Sistan and Baluchestan over the past few growing seasons. The datasets have been cross-referenced with agricultural bulletins, provincial reports, and technical publications to ensure reliability and accuracy. Following data acquisition, a series of quantitative analyses were conducted to derive final figures for economic costs, environmental emissions, and material losses. All calculations were standardized on a per-hectare basis, which is the conventional unit of analysis in Iranian agronomic reporting. To ensure data reliability, triangulation was performed using provincial reports, academic publications, and expert validation by regional agronomists.

To structure the analysis, each crop was considered a discrete Quantity Center (QC), consistent with ISO 14051 guidelines for MFCA application. Within each QC, the flow of materials and energy was assessed from the initial stage of land preparation through planting, crop maintenance, irrigation, fertilization, and harvesting. Due to the absence of sharp boundaries between intermediate stages in these open-field cropping systems, and considering that most resource inputs are applied continuously or cyclically, the entire production cycle was modeled as a single functional unit for each crop. This modeling approach allows for an integrated and system-wide view of the resource flows and cost drivers involved (Bux and Amicarelli, 2022).

In each production system, both positive outputs (harvested crop yields) and negative products (material losses, emissions, and yield loss) were tracked. Positive outputs were measured in kilograms per hectare (kg ha^{-1}), while negative products were accounted for in both physical units (kg, m^3, kWh) and monetary values (USD ha^{-1}). Inputs included chemical fertilizers (nitrogen, phosphate, potassium), organic fertilizers (primarily farmyard manure), pesticides and herbicides, irrigation water, diesel fuel, electricity, human labor, and the use of machinery. The cost of each input was derived from official market rates or average regional prices as reported by the Ministry of Agriculture and provincial cooperatives.

Material flow analysis began by quantifying each input in its physical unit. For example, the nitrogen application rate for wheat was expressed in kilograms per hectare, the volume of irrigation water for watermelon was estimated in cubic meters per hectare, and pesticide application for tomato and onion was measured in liters or kilograms depending on formulation. The energy content of diesel and electricity used for irrigation pumping or machinery operation was converted to kilowatt-hours (kWh) and standardized across all crops. This allowed for consistent tracking and comparison of energy use efficiency. The energy embedded in each input and output is quantified using specific coefficients. These coefficients are applied to the physical measurements of the inputs to calculate their energy content, as detailed in Table 1.

Table 1. Energy coefficients

Energy flow	Unit	Energy coefficients (MJ $Unit^{-1}$)	References
Diesel fuel	L	47.8	(Mousavi-Avval et al., 2011)
Human labor	h	1.96	(Mousavi-Avval et al., 2011)
Machinery	kg	142.7	(Mousavi-Avval et al., 2011)
Nitrogen	kg	66.14	(Afshar and Dekamin, 2022)
Phosphate (P_2O_5)	kg	12.44	(Dekamin et al., 2025b)
Sulfur (S)	kg	1.12	(Mousavi-Avval et al., 2011)
Potassium (K_2O)	kg	11.15	(Mousavi-Avval et al., 2011)
Herbicide	kg	238	(Mousavi-Avval et al., 2011)
Insecticide	kg	101.2	(Mousavi-Avval et al., 2011)
Irrigation water	m^3	1.02	(Acaroğlu, 1998)
Electricity	kWh	11.93	(Dekamin et al., 2025c)
Negative output			
Irrigation water	m^3	1.02	(Acaroğlu, 1998)
Ammonia (NH_3)	kg	2.7	(Afshar and Dekamin, 2022)
Nitrate (NO_3)	kg	12.44	(Afshar and Dekamin, 2022)
Phosphorus	kg	3.32	(Afshar and Dekamin, 2022)
Insecticide	kg	101.2	(Mousavi-Avval et al., 2011)
Herbicide	kg	238	(Mousavi-Avval et al., 2011)
Yield loss	kg	Different	(Mousavi-Avval et al., 2011)

When assessing the total embodied energy within agricultural machinery, the calculation accounts for the gradual dissipation of this energy over the machinery's 10-year economic lifespan, according to Equation 1.

$$\text{TME (MJ ha}^{-1}\text{)} = ((\text{MW (kg)} + \text{IW (kg)}) \times \text{ME (MJ kg}^{-1}\text{)} \times \text{WT (h ha}^{-1}\text{)}) / \text{MEL (h)} \quad \text{(Eq.2)}$$

In this context, ME signifies the energy associated with machinery, MW indicates the weight of the machinery, WT represents the machine's operational time, and MEL denotes the economic lifespan of the machinery.

The energy attributed to irrigation water corresponds to the energy invested in constructing infrastructure such as dams, pipelines, pumps, and irrigation systems. To determine the coefficients for adverse effects resulting from chemical fertilizer usage, the Standard Entropy of Formation method was employed (Afshar and Dekamin, 2022).

The monetary conversion of physical flows was performed by multiplying each input's physical quantity by its unit price. In MFCA, this step is critical as it reveals the cost impact of inefficiencies, especially in cases where resource losses are high or input prices are volatile. For example, excess application of nitrogen fertilizer not only leads to environmental emissions but also represents a direct financial loss, particularly when crop uptake is suboptimal. By calculating both the total input costs and the value of lost materials, MFCA provides a detailed breakdown of how inefficiencies translate into real monetary consequences.

For environmental emissions, only on-farm emissions were considered, consistent with the MFCA scope. These include emissions generated directly through crop production activities, such as nitrate leaching into groundwater, ammonia volatilization from fertilizer application, and pesticide residue emissions to air, water, and soil. Off-farm emissions, such as those arising from the manufacture of fertilizers or transport of inputs, were excluded from the system boundary, as farmers have limited control over these factors. The inclusion of on-farm emissions allows the study to focus on farm-level management practices and their direct consequences.

To quantify emissions, established emission factors from internationally recognized sources (e.g., IPCC guidelines, PestLCI 2.0 model) were applied (Table 2). For instance, ammonia emissions from farmyard manure were calculated using conversion coefficients per kilogram of application, while nitrate leaching was estimated based on typical leaching rates under flood and drip irrigation practices. Pesticide emissions were modeled using the PestLCI 2.0 tool, adapted to open-field crops in arid climates. These emission values were then translated into monetary terms using cost estimates derived from studies on environmental damage and pollution mitigation costs in agricultural contexts.

In addition to direct emissions, yield losses were accounted for as a form of negative product in the MFCA framework. Yield loss can occur due to pest infestation, disease pressure, irrigation lapses, or climatic stress. These losses were estimated as the difference between potential and actual yields, adjusted for regional yield expectations under good management practices. The economic cost of yield loss was calculated by multiplying the lost volume (kg ha^{-1}) by the average market price of each crop at harvest.

The economic performance of each crop was evaluated using four main indicators:

1. Gross Value of Production (GVP), calculated as the total yield (kg ha^{-1}) multiplied by unit market price (USD kg^{-1});
2. Gross Return (GR), which subtracts variable costs (excluding fixed capital and land) from GVP;
3. Benefit-Cost Ratio (BCR), the ratio of GVP to total costs (including environmental costs under MFCA);
4. Economic Productivity (EP), defined as yield per dollar of variable cost (kg USD^{-1}) (Table 3).

Table 2. Coefficients used in calculating the emissions from fertilizers (Eggleston et al., 2006).

Characteristics		Coefficient
Emissions from fertilizers	$\frac{kg\ NO - N}{kg\ N_{in}\ chemical\ fertilizer\ applied}$	0.012 (to air)
	$\frac{kg\ NO_3^- - N}{kg\ N_{in}\ chemical\ fertilizer\ applied}$	0.3 (to water)
	$\frac{kg\ CO_2\ - C}{kg\ Urea - N}$	1.57 (to air)
Conversion of emissions		
$kg\ CO_2\ - C$ to kg CO_2	$\frac{44}{12}$	
$kg\ N_2O - N$ to kg N_2O	$\frac{44}{28}$	
$kg\ NH_3 - N$ 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	$\frac{62}{142}$	
$kg\ N$ to kg NO_2	$\frac{46}{14}$	

Table 3. Economic and energy indicator in crop production (Afshar and Dekamin, 2022).

Main criteria	Sub-criteria	Unit	Calculation formulas*
Economic	Gross Value of Production (GVP)	$\$ ha^{-1}$	$GVP = Y(kg\ ha^{-1}) \times P(\$\ kg^{-1})$
	Gross return (GR)	$\$ ha^{-1}$	$GR = GVP\ (\$\ ha^{-1})\text{-Variable } Costs\ (\$\ ha^{-1})$
	Benefit/cost ratio (CBR)	Ratio	$CBR = GVP\ (\$\ ha^{-1})\ /\ TC\ (\$\ ha^{-1})$
	Economic productivity (EP)	$kg\ \$^{-1}$	$EP = Y(kg)\ /\ \text{Variable Costs}\ (\$)$
Energy	Energy productivity (EP)	$kg\ MJ^{-1}$	$EP = \frac{Yeild\ (kg\ ha^{-1})}{IE\ (MJ\ ha^{-1})}$
	Energy use efficiency (energy ratio) (EUE)	Ratio	$EUE\ (ER) = \frac{OE\ (MJ\ ha^{-1})}{IE\ (MJ\ ha^{-1})}$
	Net energy (NE)	$MJ\ ha^{-1}$	$NE = OE\ (MJ\ ha^{-1}) - IE\ (MJ\ ha^{-1})$
	Specific energy (SE)	$MJ\ kg^{-1}$	$SE = \frac{IE\ (MJ\ ha^{-1})}{Y\ (kg\ ha^{-1})}$

*Y is crop yield (kg ha^{-1}), P is Grape price ($ kg^{-1}), VC stands for variable costs ($ ha^{-1}), and TC is total costs ($ ha^{-1}), IE is energy input (MJ ha^{-1}), and OE stands for energy output (MJ ha^{-1})

Each of these indicators was calculated twice; once under the Traditional Cost Accounting (TCA) method, and once under MFCA. While TCA includes only explicit financial costs and overlooks material inefficiencies and environmental externalities, MFCA incorporates a broader perspective by assigning costs to all physical losses and emissions. This comparative approach allows for an evaluation of how traditional accounting systems might underestimate true production costs and misguide decision-making.

To maintain transparency and consistency, all data transformations, assumptions, and coefficients used in the calculations were documented and subjected to sensitivity checks. Although no direct statistical sampling was conducted, the use of national datasets and regional agricultural norms ensured a high degree of representativeness. The fact that these data are derived from official government sources also enhances the credibility and potential replicability of the methodology (19).

In terms of data normalization and comparison, all variables were expressed on a per-hectare basis, and monetary values were converted to USD using the average exchange rate during the study period. Sensitivity to inflation was mitigated by using multi-year average prices for inputs and outputs, which reduces the bias introduced by short-term price fluctuations. Where regional price discrepancies existed (e.g., different water tariffs in various parts of the province), weighted averages were used (20).

This methodology allowed for the development of a comprehensive input-output matrix for each crop, which served as the basis for further analysis. The final output of the method included:

- Physical quantities and costs of all input materials;
- Quantified emissions and their monetary impacts;
- Total output (marketable product and yield loss);
- Economic performance indicators under both MFCA and TCA;
- Comparative rankings of crop sustainability across economic and environmental dimensions.

The use of MFCA in this context provides not only a diagnostic tool for understanding the inefficiencies of current practices but also a foundation for recommending targeted interventions. For instance, if tomato production was found to have high pesticide emissions and poor BCR, strategies such as integrated pest management (IPM) or biological controls could be prioritized. Similarly, if wheat showed low GVP but high EP, its role in low-cost, low-risk farming systems could be reinforced in regional planning.

In summary, the methodology adopted in this study aligns with international best practices for environmental and economic accounting in agriculture, while being tailored to the specific socio-ecological conditions of Sistan and Baluchestan Province. It combines the rigor of standardized analytical tools (MFCA, emission modeling) with the practical relevance of context-specific data. The resulting analysis aims to provide a balanced view of crop viability, taking into account not only market returns but also environmental sustainability and input-use efficiency. By offering this dual lens, the study seeks to contribute to the ongoing transformation of agricultural systems in Iran toward more resilient, resource-conscious, and climate-adaptive practices.

3. Results and Discussion

This section presents a comprehensive evaluation of the performance of four key crops wheat, tomato, onion, and watermelon cultivated in the arid conditions of Sistan and Baluchestan Province. The analysis is based on the MFCA approach, integrating physical and economic data to assess resource efficiency, energy flows, environmental losses, and financial viability. All results are expressed on a per hectare basis to ensure consistency and comparability (Table 4).

The comparative data indicate substantial variability in input use among the four crops, reflecting differing agronomic requirements and management practices. Tomato and onion production exhibit the highest levels of human labor, with 506.0 and 446.5 h ha^{-1}, respectively, suggesting their labor-intensive nature due to activities such as transplanting, pruning, and harvesting. In contrast, wheat requires significantly less labor (107.4 h ha^{-1}), indicating a more mechanized or extensive production system. Regarding chemical fertilizer usage, tomato again demonstrates the highest consumption of nitrogen (630.6 kg ha^{-1}) and phosphate (422.9 kg ha^{-1}), aligning with its high yield potential and nutrient demand. Interestingly, potassium input is absent in tomato production, possibly due to localized soil nutrient sufficiency or fertilization strategies.

Biocide usage—comprising herbicides, insecticides, and fungicides—also shows crop-specific trends. Onion and tomato receive relatively high levels of chemical treatments, particularly in terms of insecticides and fungicides, which may be due to their susceptibility to pests and fungal diseases. For instance, tomato uses 2.7 kg ha^{-1} of insecticides and 0.7 kg ha^{-1} of fungicides. Wheat, on the other hand, receives minimal biocide application, suggesting either lower pest pressure or a more integrated pest management approach. Diesel fuel consumption varies moderately across the crops, with wheat having the highest at 82.1 kg ha^{-1}, likely reflecting increased use of mechanized field operations. Electricity use is confined to onion and wheat cultivation, possibly due to groundwater pumping for irrigation, whereas tomato and watermelon appear to rely on alternative water sources or gravity-fed systems.

In terms of positive outputs, onion, tomato, and watermelon are high-yielding crops, producing 34851.9, 29492.9, and 28617.5 kg·ha^{-1}, respectively. Wheat, in contrast, yields significantly less at 1,881.6 kg·ha^{-1}, which is expected given the nature of cereal crops and the local agro-ecological conditions. Yield losses interpreted as negative outputs are highest in tomato (1769.6 kg ha^{-1}) and watermelon (1430.9 kg ha^{-1}), indicating potential inefficiencies in harvesting, handling, or disease management. Onion and wheat also experience yield losses, though at slightly lower levels (1742.6 and 169.9 kg ha^{-1}, respectively), suggesting room for improvement in post-harvest practices and crop protection strategies. The analysis of negative outputs reveals important insights into environmental impacts associated with each crop. Tomato and onion production result in considerable nitrogen and nitrate losses to air and water, reflecting their high fertilizer input levels. For example, onion emits 51.7 kg ha^{-1} of NH$_3$ (from chemical fertilizers) and 57.6 kg ha^{-1} of nitrate to water. Similarly, tomato emits 43.1 kg ha^{-1} of NH$_3$ and 48.2 kg ha^{-1} of nitrate. These figures raise concerns about nutrient use efficiency and water pollution. Biocide-related emissions to air, water, and soil are highest in watermelon and wheat, particularly in soil contamination (7.2 and 5.8 kg ha^{-1}, respectively), pointing to potential risks for soil health and biodiversity. These findings highlight the need for integrated nutrient and pesticide management to enhance sustainability in crop production systems. Similar results have been reported in the MFCA of soybean production, where losses of soybeans, nitrogen, and irrigation water accounted for 36%, 33%, and 23% of the negative outputs, respectively. The share of other components in this study was also negligible (Dekamin and Barmaki, 2019). Comparable findings have been observed in the production of maize (Afshar and Dekamin, 2022), canola (Dekamin, 2021), and grapes (Dekamin and Kheiralipour, 2023).

3.1. Energy Use in Crop Production Systems

Energy consumption patterns across the four cropping systems revealed substantial variations, both in total energy input and in the form and origin of energy consumed. The data reveal notable differences in the energy profiles of the four crops (Table 5 and Figure 1). Onion and wheat utilize higher amounts of direct energy (6255 and 8873 MJha^{-1}, respectively), primarily due to significant diesel and electricity use, particularly for irrigation and mechanized operations. Tomato and watermelon rely less on direct energy (3 748 and 3 477 MJha^{-1}), suggesting a relatively lower dependence on mechanization and fossil fuel–based activities. Indirect energy comprising machinery, fertilizers, FYM, and biocides dominates the total input for all crops, especially for tomato (49138 MJha^{-1}), indicating a high input intensity in terms of agrochemicals and compost use.

Table 4. input-output material flow for selected crops

			Crops			
			Onion	Wheat	Tomato	Watermelon
Inputs	Human labor	hour	446.5	107.4	506.0	157.8
	Agricultural machinery	kg	6.3	10.9	6.8	7.1
	Nitrogen	kg	387.9	217.7	630.6	289.6
	Phosphate	kg	163.5	82.0	422.9	86.8
	Potassium	kg	70.6	25.5	0.0	9.2
	FYM	kg	2500.0	1414.2	3800.0	4060.0
	herbicide	kg	1.5	0.0	0.4	0.6
	insecticide	kg	0.0	0.1	2.7	1.6
	Fungicides	kg	1.0	0.0	0.7	0.7
	Diesel fuel	kg	40.3	82.1	49.0	56.3
	Electricity	kg	260.5	338.4	0.0	0.0
Positive Output	Yield	kg	34851.9	1881.6	29492.9	28617.45
Negative Inputs	NH$_3$ by FYM to air	kg	1.9	11.3	1.9	2.1
	NH$_3$ by chemical fertilizers to air	kg	51.7	31.4	43.1	1.8
	N$_2$O to air	kg	6.8	4.8	5.7	0.4
	Nitrate to water	kg	57.6	40.5	48.2	3.1
	Phosphate to water	kg	2.9	3.2	1.5	0.5
	Emissions by biocides to air	kg	0.4	0.7	0.3	0.9
	Emissions by biocides to water	kg	0.2	0.3	0.2	0.4
	Emissions by biocides to soil	kg	3.2	5.8	2.8	7.2
	Yield loss	kg	1742.6	169.9	1769.6	1430.9

Table 5. Energy forms and indices consumed in wheat, tomato, onion, and watermelon production (MJ ha^{-1})

A. Energy forms	**Unit**	**Equation**	**MFCA Onion**	**Wheat**	**Tomato**	**Watermelon**
Direct energy (DE)	MJ	Human labor + diesel fuel + electricity + seed	6255	8873	3748	3477
Indirect energy (IDE)	MJ	Machinery + chemical fertilizers + FYM + biocides	29715	16825	49138	22392
Renewable energy (RE)	MJ	Human labor + FYM +seed	1625	635	2132	1527
Non-renewable energy (NRE)	MJ	Machinery + chemical fertilizers + diesel fuel+ biocides + electricity	34737	25744	51182	24787
B. Energy flow						
Input Energy	MJ		35969	25698	52886	25869
Output Energy	MJ		23714	33369	22264	21609
Positive energy	MJ		27882	35153	23594	22894
Negative energy	MJ		4167	1784	1330	1285
C. Energy indices						
Energy ratio (ER)		Output energy (MJ ha $^{-1}$)/Total input energy (MJ ha $^{-1}$)	0.66	1.30	0.42	0.84
Energy productivity (EP)	kg MJ^{-1}	Crop yield (kg ha $^{-1}$)/Total input energy (MJ ha $^{-1}$)	0.97	0.09	0.56	1.11
Specific energy (SE)	MJ kg^{-1}	Total input energy (MJ ha $^{-1}$)/Crop yield (kg ha $^{-1}$)	1.03	10.59	1.79	0.90
Net energy (NE)	MJ	Output energy (MJ ha $^{-1}$)/Total input energy (MJ ha $^{-1}$)	-12255.11	7671.51	-30622.44	-4260.07

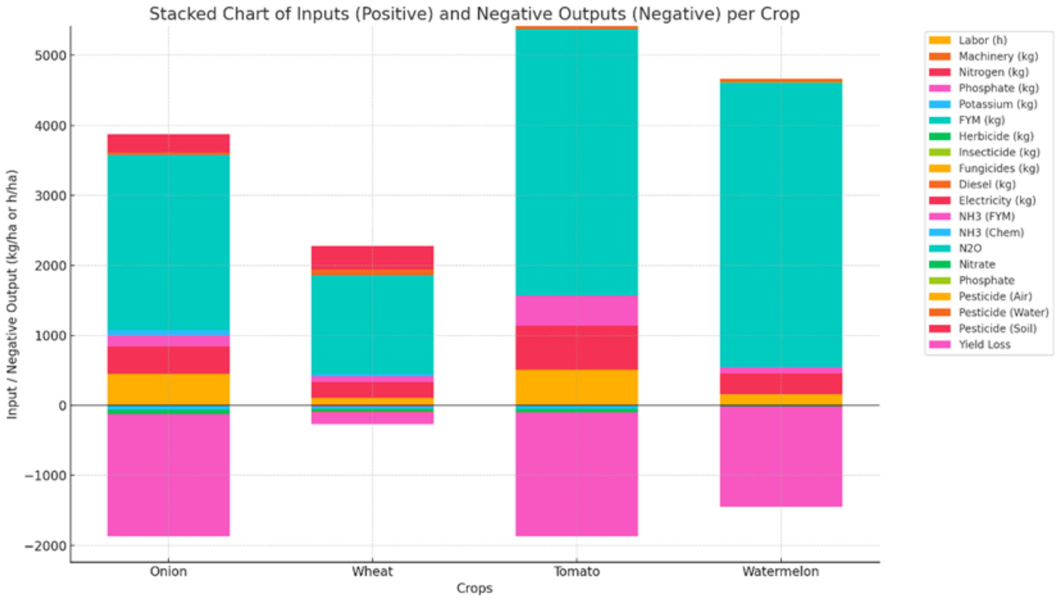

Figure 1. Energy input vs output comparison among crops (MJ ha⁻¹)

Tomato cultivation, despite achieving high yields, incurred the highest total input energy (52886 MJ ha^{-1}), much of which was indirect energy embedded in fertilizers and chemical inputs. In contrast, watermelon, with a total input of 25869 MJ ha^{-1}, demonstrated significantly lower energy consumption while still achieving favorable yield outcomes, hinting at its superior input-output balance.

When categorizing energy into renewable and non-renewable forms, it is evident that all four cropping systems are heavily reliant on non-renewable sources. Tomato production exhibits the highest non-renewable energy use (51182 MJ ha^{-1}), while wheat and watermelon follow with 25744 and 24787 MJ ha^{-1}, respectively. Renewable energy input is relatively minor across all crops, with tomato again leading at 2,132 MJ ha^{-1}. Onion has a slightly higher proportion of renewable input (1,625 MJ ha^{-1}) compared to wheat (635 MJ ha^{-1}), largely attributable to FYM and human labor. These results underscore the need to shift towards more renewable-based practices to enhance sustainability.

Tomato has the highest total input energy (52 886 MJ ha^{-1}) but a relatively low output energy (22264 MJ ha^{-1}), leading to an unfavorable energy balance. Wheat, conversely, demonstrates an efficient energy flow, with lower input (25698 MJ ha^{-1}) and higher output (33369 MJ ha^{-1}), resulting in a positive net energy return. Onion and watermelon present intermediate profiles. Onion's input (35969 MJ ha^{-1}) surpasses its output (23714 MJ ha^{-1}), indicating inefficiency, while watermelon's figures are more balanced (input: 25869 MJ ha^{-1}; output: 21609 MJ ha^{-1}), though still slightly negative in net terms (Figure 2).

The MFCA approach distinguishes between productive (positive) and unproductive (negative) energy use. In this context, tomato records the lowest negative energy value (1330 MJ ha^{-1}), despite its overall inefficiency. Wheat shows minimal negative energy (1784 MJ ha^{-1}), highlighting its relative operational effectiveness. Onion, on the other hand, has the highest negative energy flow (4167 MJ ha^{-1}), indicating substantial losses, possibly from post-harvest waste, emissions, or unutilized inputs. These differences provide critical insights for optimizing resource efficiency and reducing waste in crop systems.

Energy ratio (ER), energy productivity (EP), and specific energy (SE) are crucial indicators of energy use efficiency. Wheat achieves the highest energy ratio (1.30), denoting that its energy output exceeds its input a sign of excellent efficiency. In contrast, tomato performs poorly, with an ER of just 0.42, indicating significant energy loss.

Watermelon has a moderate ER of 0.84, while onion trails at 0.66. Regarding energy productivity, watermelon leads with 1.11 kg MJ^{-1}, meaning it produces more yield per unit of energy input. Specific energy analysis reveals that wheat requires the most energy per unit of yield (10.59 MJ kg^{-1}), while watermelon is the most energy-efficient (0.90 MJ kg^{-1}).

Net energy (NE), defined as the difference between output and input energy, provides a direct measure of energy gain or loss. Wheat is the only crop with a positive NE (+7671.51 MJ ha^{-1}), reaffirming its efficiency in both agronomic and energy terms. Tomato shows the most substantial energy deficit (-30622.44 MJ ha^{-1}), making it the least energy-efficient system among the four. Onion and watermelon also show negative net energy values (-12255.11 and -4260.07 MJ ha^{-1}, respectively).

These findings suggest that targeted improvements in energy management particularly reducing non-renewable inputs and post-harvest losses are essential for transitioning towards sustainable crop production systems.

Pahlavan et al. (2011) and Yelmen et al. (2019) identified electricity and chemical fertilizers as the main energy inputs in tomato production. Previous studies (Kuswardhani et al., 2013; Yelmen et al., 2019; Dimitrijević et al., 2015; Esengun et al., 2007; Moghaddam et al., 2011; Hatirli et al., 2006; Nasirpour et al., 2023) have reported input energy values for open-field tomato cultivation ranging from 47,647 to 106,716 MJ per hectare, and output energy values ranging from 41,943 to 136,000 MJ ha^{-1}.

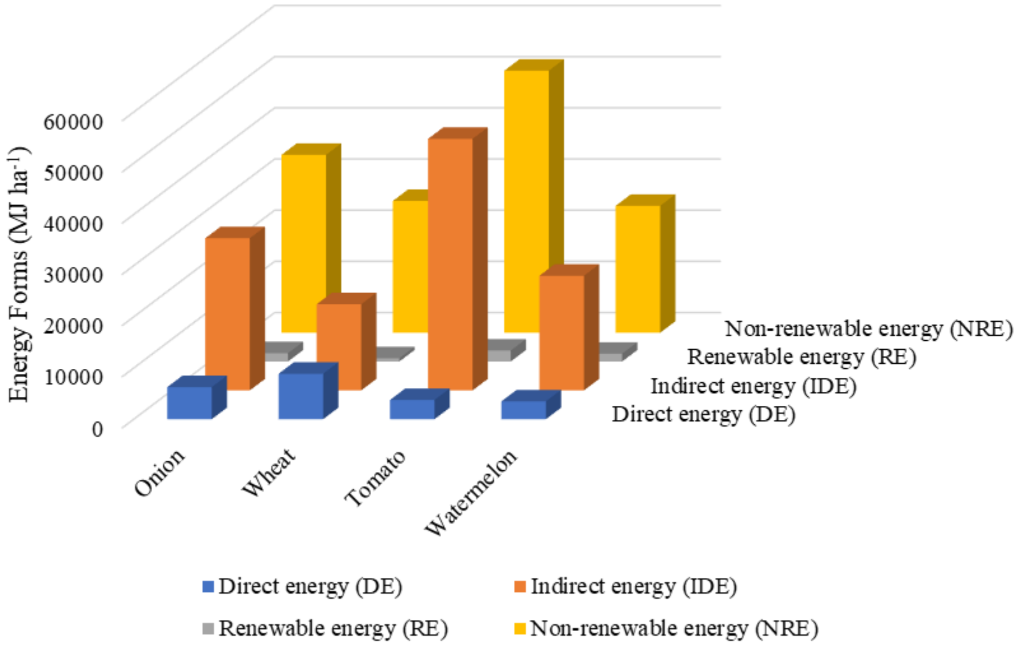

Figure 2. Energy forms consumed in wheat, tomato, onion, and watermelon production

3.2. Economic Indicators and Production Efficiency

Turning to financial performance, results shown in Table 6 provide a comparative analysis of economic outcomes using MFCA framework. onion exhibited the highest GVP at \$7352.7 ha^{-1}, far surpassing wheat (\$ 681.6 ha^{-1}), tomato (\$5337.6 ha^{-1}), and watermelon (\$3114.6 ha^{-1}). This was primarily driven by its high market price (\$0.2 kg^{-1}) and respectable yield (34851.9 kg ha^{-1}).

Table 6. Key economic indicators for crop production systems

Indicator	Unit	Equation	Onion	Wheat	Tomato	Watermelon
Yield (Y) or Positive product	kg ha^{-1}		34851.9	2427.7	29492.9	28617.0
Sale price (CP)	\$kg^{-1}		0.2	0.2	0.15	0.10
Production Cost (PC)	\$		585.1	187.1	739.4	285.8
Gross value of production (GVP)	\$	GVP=Y*CP	7352.7	681.6	5337.6	3114.6
Negative product (NP)	\$		382.3	196.1	913.7	252.9
Gross return (GR)	\$	GR=GVP-PC	6767.5	494.5	4598.2	2828.9
Benefit to cost ratio (BCR)		BCR=GVP.PC	12.6	3.6	7.22	10.9
Economic productivity (EP)	kg \$	EP=Y.PC	59.6	13.0	39.9	100.1

Wheat, although crucial for food security, yielded only 2427.7 kg ha^{-1} and fetched \$0.2 per kg, making it the least profitable in absolute terms.

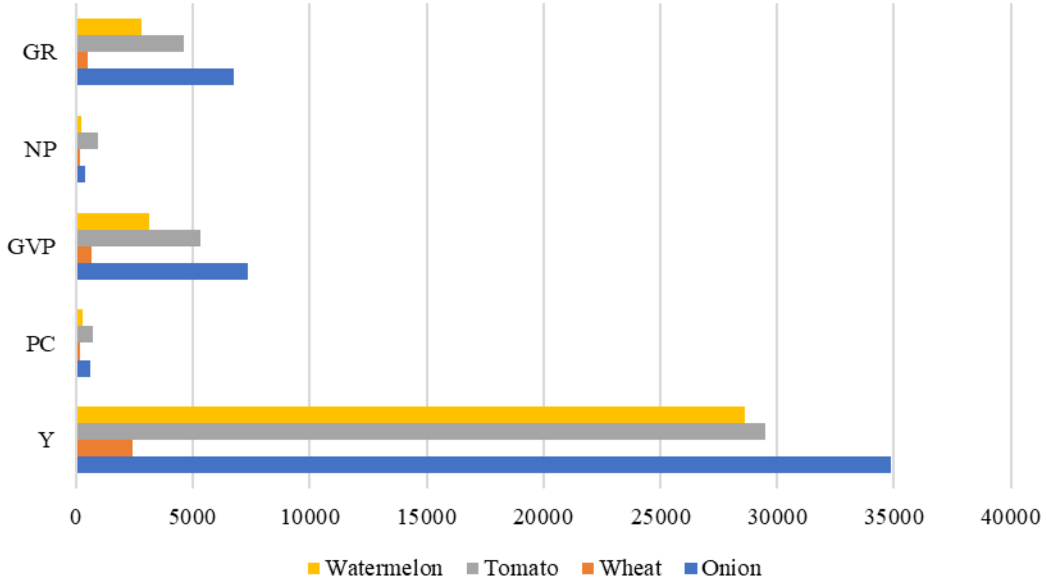

Figure 3. Gross return (GR), negative product (NP), gross value of production (GVP), production cost (PC) and yield (Y) across different crops

When considering GR, which accounts for production costs, onion remained dominant with $6767.5 ha⁻¹, followed by tomato ($ 4598.2ha⁻¹). watermelon and wheat lagged behind with returns of $2828.9 ha⁻¹ and $494.5 ha⁻¹ respectively (Figure 3).

A deeper look at BCR reveals important nuances. While onion recorded an outstanding BCR of 12.6, its high BCR reflects not just its yield and price but also its relatively low production cost ($585.1 ha⁻¹). Watermelon also performed strongly (BCR: 10.9), followed by Tomato (15.43) and wheat (10.10), all indicating economically viable operations under current cost structures.

EP, defined as yield per unit of cost ($), echoed this trend. Watermelon achieved the highest EP (100.1 kg $⁻¹), followed by onion (59.6), tomato (39.9), and wheat (13). These results suggest that, per dollar invested, watermelon delivers the most biomass, reinforcing its role as a high-efficiency crop.

However, under MFCA, additional hidden costs especially those related to waste, emissions, and inefficiencies are integrated into the financial analysis. As illustrated in Table 6, tomato and onion exhibited the highest negative product costs, at $913.7 ha⁻¹ and $382.3 ha⁻¹ respectively. These costs represent material and energy losses, environmental damage, and post-harvest inefficiencies, which are often neglected in conventional accounting. The contrasting profiles of the four crops indicate a clear trade-off between profitability, energy efficiency, and environmental performance. Onion, while delivering unmatched economic returns, also incurs the highest environmental cost and material losses. Its high yield per dollar spent and positive energy balance make it ideal for commercial production, but it requires effective post-harvest handling and water management to avoid waste and mitigate resource stress. Watermelon appears to be a balanced crop, with positive energy metrics and moderate profitability. Its relatively low input requirements and environmental impact make it suitable for resource-constrained farmers or areas with limited access to irrigation.Tomato is a high-return, high-risk crop. Despite strong financial metrics, it is heavily dependent on external inputs, and its poor energy efficiency and significant negative products raise sustainability concerns. Investment in integrated pest management (IPM) and efficient irrigation systems is crucial to maintain its long-term viability.Wheat, despite its limited economic appeal, offers stability and low-cost cultivation. It remains important for subsistence farming and strategic food security, particularly under conditions of market volatility or limited access to inputs. However, its low energy and economic productivity suggest that it is best suited as a complementary crop in diversified farming systems.

The findings of this study provide important insights for policymakers, extension agents, and farmers. Firstly, MFCA proves to be a valuable tool in unveiling the full spectrum of costs associated with crop production not just in financial terms but in terms of material and energy efficiency. Traditional accounting systems overlook these inefficiencies, potentially leading to suboptimal decision-making at both the farm and policy levels. Secondly, in a region like Sistan and Baluchestan, where water is the limiting factor and energy inputs are largely fossil-based, crops like tomato, watermelon, and onion with high energy returns and efficient resource use should be prioritized in resource allocation policies. Water pricing schemes, targeted subsidies, and training programs should encourage the adoption of such crops under water-saving cultivation methods like drip irrigation. Thirdly, environmental costs such as emissions and nutrient leaching need to be accounted for in long-term sustainability planning. MFCA can be institutionalized in provincial agricultural planning to internalize environmental externalities into economic calculations, pushing for greener technologies and better land-use practices. Lastly, for smallholder farmers, the results suggest that crop choice must align with farm capacity. While onion offers the highest returns, it may not be feasible without access to post-harvest storage, labor, and capital. wheat provide safer, lower-cost alternatives that ensure food security with minimal environmental degradation.

4. Conclusion

Agricultural production in arid and semi-arid regions faces a growing set of challenges, from escalating input costs and resource scarcity to environmental degradation and socio-economic vulnerability. In Iran's Sistan and Baluchestan Province, these challenges are especially pronounced due to extreme climatic conditions, limited water resources, and fragile rural infrastructures. Against this complex backdrop, this study applied the MFCA methodology to analyze and compare the performance of four major crops wheat, tomato, onion, and watermelon across both economic and environmental dimensions. The study's findings offer critical insights for advancing sustainable agriculture in water-stressed, input-limited, and economically diverse contexts. The application of MFCA revealed a number of key observations that would likely remain hidden in conventional cost accounting systems. By tracing both physical flows and financial costs associated with inputs, outputs, emissions, and inefficiencies, MFCA provided a nuanced picture of how each crop performs in real-world conditions. The results clearly demonstrated that economic profitability does not always align with environmental sustainability, and that decision-making in agriculture must account for a broader spectrum of performance indicators if long-term resilience is to be achieved.

Among the studied crops, onion emerged as the highest-performing crop economically, achieving a gross value of production exceeding \$7352 ha^{-1}, an exceptionally high BCR of 12.6, and a strong EP of 59.6kg \$$^{-1}$. Its energy profile was equally impressive, with a net energy gain of -12255.11MJ ha^{-1} and an ER of 0.66, indicating outstanding energy efficiency. These figures suggest that onion offers not only the highest return on investment but also strong energy returns per unit of input. However, its negative product cost, reflecting material losses and environmental costs, was also the highest among the four crops. This suggests that the very factors contributing to onion's productivity such as intensive water and fertilizer use also generate substantial inefficiencies and ecological burdens. Therefore, to fully harness onion's potential, interventions are needed to minimize waste, improve irrigation efficiency, and reduce post-harvest losses, particularly in the absence of adequate storage infrastructure. Watermelon, by contrast, presented the most balanced performance. It demonstrated a positive net energy value, an energy ratio close to 1, and moderate economic returns. While its gross value of production and profitability were lower than tomato or onion, it exhibited low production costs, a reasonable BCR (10.9), and low environmental impacts. These characteristics make watermelon a strong candidate for sustainable agriculture in the province, particularly in farming systems constrained by access to capital, labor, or external inputs. Furthermore, watermelon's storage flexibility and moderate water demand add to its resilience and utility across different climatic zones and seasonal cycles. Tomato presented a complex and somewhat paradoxical case. It generated high net profits and a CR exceeding 7.22, but its energy efficiency was poor, with a negative net energy balance and the lowest energy ratio of all crops. Tomato was also associated with relatively high negative product costs, especially in the form of pesticide losses, input overuse, and post-harvest deterioration. Despite its economic appeal, these inefficiencies raise concerns about the crop's long-term viability in resource-constrained environments. The findings point to the necessity of adopting integrated pest management (IPM), efficient fertilizer application, and cold chain development as prerequisites for tomato cultivation to be truly sustainable. Wheat, long considered a cornerstone of food security in Iran, had the lowest yield, lowest gross value, and lowest economic productivity of the four crops. However, it also had low production costs and a respectable BCR, suggesting that under certain conditions such as subsistence farming, limited labor availability, or lack of market access it remains a rational choice. More importantly, wheat serves strategic and socio-political functions that go beyond market profitability. Its integration into regional cropping systems should thus be framed within a broader food security agenda, rather than viewed purely through economic or environmental lenses.

Taken together, these results underscore the multi-dimensional nature of crop selection and resource allocation in dryland agriculture. No single crop can be considered universally optimal across all criteria. Instead, each crop offers a unique set of trade-offs:

- Onion is highly profitable and energy-efficient but environmentally demanding.
- Watermelon is moderately profitable and environmentally sustainable.
- Tomato is profitable but energy- and resource-intensive.
- Wheat is low-input, low-output, and food security–oriented.

From a policy perspective, this implies that contextual crop prioritization is essential. In areas with reliable market access and capital availability, watermelon and onion may offer pathways to rural income generation, especially if production is coupled with efficient post-harvest handling systems. In contrast, wheat may be preferable in regions where sustainability, stability, and minimal input dependency are paramount.

The study also validates MFCA as a valuable analytical framework for agricultural sustainability assessment. Unlike traditional models that focus exclusively on profit or yield, MFCA incorporates hidden environmental costs and inefficiencies, encouraging a life-cycle mindset even at the farm level. This makes MFCA a potentially transformative tool for agricultural extension agents, farm cooperatives, and policy planners seeking to implement climate-smart agriculture.

For effective integration of MFCA into mainstream agricultural decision-making, the following recommendations are proposed:

- Institutionalization of MFCA in agricultural planning: National and provincial planning bodies should adopt MFCA guidelines as a standard part of project appraisal, subsidy allocation, and sustainability assessment.
- Training and capacity-building: Agricultural extension services should train farmers and field officers in basic MFCA concepts and applications, using tools such as simplified flow charts and digital calculators.
- Data infrastructure development: To reduce dependency on field surveys, a centralized database integrating crop-specific MFCA parameters including emission coefficients, energy use patterns, and economic baselines should be developed and maintained.
- Crop-specific sustainability policies: Based on MFCA findings, targeted policies can be crafted—for example, promoting onion cultivation in water-scarce areas, or regulating tomato pesticide usage in high-input zones.
- Incentivization of input-efficient technologies: Financial and technical support for low-energy irrigation systems (e.g., solar-powered drip systems), biodegradable inputs, and waste-reducing post-harvest systems can enhance overall sustainability across crops.

This study relies on secondary data sources compiled from peer-reviewed literature and official agricultural databases, which may introduce variability due to differing measurement protocols and temporal coverage. Off-farm emissions associated with post-harvest processes such as processing, packaging, and transportation were not included in our material flow and energy balances. Future work should incorporate primary field measurements to validate MFCA parameters, extend the system boundary to capture the full supply chain, and perform farm-level cost–benefit assessments under varying water-scarcity scenarios. These enhancements will strengthen the robustness of resource-efficiency evaluations and better inform policy mechanisms.

In conclusion, this study highlights the need to go beyond surface-level metrics in evaluating agricultural productivity. By integrating environmental and economic lenses through the MFCA framework, it becomes possible to identify not just the most profitable crops, but the most sustainable and resilient ones. Such a dual-perspective approach is indispensable for developing climate-resilient, resource-efficient, and economically inclusive agricultural systems in fragile environments like Sistan and Baluchestan and in similar agroecological zones around the world.

Author Note

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