Assessing the Economic–Environmental Trade-off of Crop Rotations: A Case Study of Mung Bean Production

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Abstract

The ecological footprint reflects human pressure on natural resources and environmental biocapacity and is widely used to assess agricultural sustainability. This study examined the effect of preceding crops (wheat, barley, and canola) on the environmental and economic performance of mung bean production. Data were collected via farmer questionnaires and interviews. Environmental indicators [ecological footprint (EF), biocapacity (BC), ecological balance (EB)] and economic indicators [gross margin, benefit–cost ratio (BCR)] were calculated. Results showed that the preceding crop significantly affected most indicators ($p < 0.05$); canola differed from wheat and barley, while wheat and barley did not differ significantly. Environmentally, mung bean after canola had the lowest total EF (1.055 gha ha^{-1}) and highest relative ecological efficiency (0.315), but the lowest BC (1.541 gha ha^{-1}). Mung bean after wheat exhibited the highest EF (1.777 gha ha^{-1}) and the highest BC (2.277 gha ha^{-1}). Although EB was positive for all rotations (0.482–0.500 gha ha^{-1}), the Ecological Footprint Index (EFI) fell within the 'weak sustainability' category (0.216–0.315), and the ratio of overexploitation footprint to input footprint (EF_{ovp}/EF_{inp}) ranged from 4.30 to 8.59, indicating that overexploitation pressure overwhelmingly dominates input-driven pressure. Economically, wheat achieved the highest gross margin ($ 1,887 ha^{-1}) and BCR (2.844), while canola gave the lowest ($ 1,032 ha^{-1}; 1.479). A composite index with adjustable ecological-economic weights revealed a trade-off threshold at $w \approx 0.55$: canola is superior under ecological priority, wheat under economic priority. Given local biocapacity, selecting wheat as the preceding crop offers the most balanced combination of EF management and profitability for mung bean production in this region.

Keywords: Agricultural cost-benefit analysis; Biocapacity; Ecological footprint; Economic efficiency; Preceding crop

Introduction

Sustainable agriculture is one of the key pillars for ensuring food security and protecting natural resources (Food and Agriculture Organization of the United Nations [FAO], 2018; Pretty & Bharucha, 2018). Achieving this goal requires the development of policies and instruments that can simultaneously ensure economic efficiency, social equity, and environmental sustainability (Food and Agriculture Organization of the United Nations [FAO], 2015; Te Wierik *et al.*, 2025). However, conducting a comprehensive assessment of sustainability in the agricultural sector has always faced methodological challenges. Conventional approaches—such as Life Cycle Assessment (LCA)—primarily focus on measuring and mitigating negative environmental impacts, while overlooking the intrinsic capacity of agricultural systems to provide positive ecosystem services, such as biodiversity conservation, soil quality improvement, and carbon sequestration (Joly *et al.*, 2024; Laurentiis *et al.*, 2024; Liu *et al.*, 2020; Nadi, Abad-Gonz´alez, & P´erez-Neira, 2026; Soldati *et al.*, 2023; Van der Werf, Knudsen, & Cederberg, 2020; Zhen *et al.*, 2025). This limitation results in an incomplete depiction of agriculture's overall environmental performance. In this context, the Ecological Footprint has been proposed as a more comprehensive indicator. Originally introduced by Rees and Wackernagel, this metric assesses the ecological balance of a system by comparing the extent of human demand on nature with nature's capacity to regenerate and respond to that demand (Rees & Wackernagel, 1994). Both indicators are expressed in global hectares (gha), enabling direct comparison between resource consumption and the biosphere's regenerative capacity (Huijbregts, Hellweg, Frischknecht, Hungerbühler, & Hendriks, 2008; Monfreda, Wackernagel, & Deumling 2004). This approach views agriculture not merely as a consumer of natural resources but as an integral component of natural capital, one that can actively contribute to the maintenance and enhancement of ecological systems (Goodland, 1995).

Over recent decades, extensive evidence has shown that the environmental pressures arising from agriculture are largely a function of consumption patterns and production practices, although their intensity and nature vary across regions. At the macro level, studies in Europe have demonstrated that while agriculture moved closer to achieving ecological balance between 2002 and 2010, financial subsidies to farmers did not necessarily lead to improved environmental sustainability, revealing the complexity of policy impacts on ecological outcomes (Passeri *et al.*, 2016). In Nigeria, despite relatively stable sustainability in many areas, the food sector has remained a major contributor to environmental pressures. A transition toward diets with higher consumption of plant-based products and reduced food waste has been proposed as a key strategy for mitigation (Passeri *et al.*, 2016). Conversely, in countries such as Brazil, urban dietary shifts toward greater consumption of ultra-processed foods have intensified environmental pressures (da Silva *et al.*, 2021). A similar trend has been observed in China, where the transition from grain-based diets to those rich in animal products has led to a significant rise in ecological pressures (Cao, Chai, Yan, & Liang 2020). In Iran as well, population growth and increased consumption of animal-based foods have amplified these pressures (Koocheki, Nasiri Mahallati, & Khorramdel 2016). Martella, La Porta, Nicastro, Biagetti, and Franco (2023) reported that, in the case of the industrial tomato supply chain in Italy, the agricultural stage at the farm level exhibited a positive ecological balance (biocapacity exceeding consumption). However, when the entire supply chain, from cultivation to processing and distribution, was considered, the overall balance turned negative. This finding underscores the necessity of supply chain–wide assessments beyond the farm level for accurately evaluating sustainability. Furthermore, recent studies in Indonesia have shown that integrating the ecological footprint framework with advanced approaches such as machine learning can serve as an effective tool for optimising resource management and reducing land deficits (Safitri, Wikantika, Riqqi, Deliar, & Sumarto, 2021). While macro-level studies reveal regional patterns and policy impacts, micro-level evidence highlights the decisive role of crop type and management practices. For instance, livestock products, particularly red meat have a substantially larger footprint compared with plant-based products (Cao *et al.*, 2020; Soltani, Soltani, Alimagham, & Zand, 2021). Moreover, input management plays a pivotal role in determining the extent of environmental pressure. Alternative agricultural systems, such as organic farming (Niccolucci *et al.*, 2008; Passeri, Borucke, Blasi, Franco, & Lazarus 2013), conservation agriculture (Naderi Mahdei, Bahrami, Aazami, & Sheklabadi 2015), and the use of manure instead of chemical fertilisers (Cerutti *et al.*, 2011), generally result in ecological footprints smaller than conventional, input-intensive systems (Nategh, Banaeian, Gholamshahi, & Nosrati 2021).

Therefore, optimising input management is more crucial for enhancing sustainability than relying solely on high-cost technological interventions (Nategh *et al.*, 2021). Studies have also shown that the economic profitability of crops does not necessarily correlate with lower environmental pressures; achieving a balance between income and sustainability requires selecting an optimal combination of crops (Blasi, Passeri, Franco, & Galli, 2016; Li *et al.*, 2020).

In Iran, numerous studies have examined the ecological footprint of agricultural products. These investigations have shown that crop type and production systems (rainfed or irrigated) are key determinants of the ecological footprint. Rainfed systems generally exhibit higher footprints due to lower yields, whereas irrigated systems place greater demands on water and energy resources (Soltani *et al.*, 2021). Among plant-based products, wheat, and among livestock products, red meat exerts the greatest pressure on natural resources (Soltani *et al.*, 2021). Case studies on saffron (Esfahani & Khazaee, 2019), tobacco (Kor, Naderi, Shanazi, & Esfahani, 2023), potato and cucumber (Rezaei, Naderi Mahdei, Karimi, & Shanazi, 2019), chickpea and lentils (Nategh *et al.*, 2021), wheat and barley (Esfahani & Javadi, 2022), and wheat and maize (Zadehdabagh, Monavari, Kargari, Taghavi, & Pirasteh 2024) all emphasise that the ecological footprint is highly sensitive to input structure and production methods. For instance, in saffron cultivation, the majority of the footprint arises from indirect, off-farm emissions, underscoring the importance of extra-farm factors, such as input production.

Overall, the findings indicate that Iranian agricultural systems face serious sustainability challenges. High consumption of chemical fertilisers, fossil fuels, and water is the primary contributor to environmental pressure. In addition, misguided support policies, such as subsidies, have further exacerbated existing sustainability problems (Esfahani & Javadi, 2022; Nategh *et al.*, 2021).

Crop rotation, as one of the key strategies for resource management, can directly influence components of the ecological footprint by improving soil quality, enhancing biological nitrogen fixation, reducing dependence on chemical fertilisers, and controlling pests. Among leguminous crops, mung bean holds a special place in the protein supply due to its nitrogen-fixing ability and high nutritional value. In addition, its relatively low water requirement compared with many other crops, high economic value, and the potential use of its residues as livestock feed are among the major advantages of mung bean cultivation in Golestan Province.

Despite the importance of crop rotation, a review of the literature reveals that most previous studies have focused on single-crop evaluations or limited comparisons, while field-based research examining the simultaneous effects of rotation on both ecological footprint and economic profitability remains scarce. Consequently, a key question remains unanswered: *How does the preceding crop affect the ecological footprint and economic viability of the subsequent crop?*

Accordingly, the present study, drawing upon the Ecological Footprint–Biocapacity (EF–BC) framework for environmental assessment and farm-level cost-benefit analysis for economic evaluation in Golestan Province, seeks to fill this research gap. The main objective is to evaluate the effect of preceding crops on (i) environmental indicators, including Ecological Footprint (EF), Biocapacity (BC), and Ecological Balance (EB), and (ii) economic indicators, including Gross Margin (GM) and Benefit–Cost Ratio (BCR), and to identify optimal rotations that balance environmental sustainability with economic efficiency.

In this regard, the study aims to address the following research questions:

1. Which cropping system results in the lowest ecological footprint in mung bean production?
2. Which cropping system achieves the highest economic profitability?
3. Which cropping system provides the best balance between footprint reduction and profitability enhancement?
4. How efficient is input use in each cropping system?

By integrating the ecological footprint with farm-level economic analysis across different crop rotations, this study moves beyond the limitations of impact-focused assessments and offers a more balanced measure of agricultural sustainability. Answering these questions can provide a solid scientific basis for designing sustainable and cost-effective cropping patterns, offering valuable guidance to farmers and policymakers. Ultimately, this study aims not only to resolve the long-standing trade-off between profitability and environmental sustainability but also to present a practical model for designing sustainable crop rotations in other comparable regions.

Materials and Methods

Study Area

This study was conducted in Golestan Province, north eastern Iran, across the area spanning between approximately 36°30′–38°08′ N and 53°57′–56°22′ E (Zanjani, 2002). The province covers approximately 20,381 km² and is bounded by the Republic of Turkmenistan to the north, North Khorasan and Semnan Provinces to the east and south, and Mazandaran Province and the Caspian Sea to the west (Zanjani, 2002). Its topography ranges from approximately 29 metres below sea level along the Caspian coast to 3,859 metres in the Alborz Mountains (Topographic-map.com, n.d.). Consequently, the province exhibits a variety of climatic conditions, including cold mountainous zones in the highlands, temperate rainforests and mixed mountain systems in the central areas, and semi-arid regions in the northern lowlands (UNESCO, n.d.). Located in the eastern Alborz range, the highest point of the province is Shavar, at 3,945 metres (Bunalski & Ghahari, 2017). This climatic and topographic diversity gives Golestan significant agricultural potential, making it suitable for a wide range of crops, including mung bean (Moghaddam, Amerian, Biabani, & Mollashahi, 2021).

Research Methodology

This study is of an applied–analytical nature and was conducted using a survey-based approach to assess the ecological footprint of mung bean production systems in Golestan Province. Data were collected through face-to-face questionnaires and interviews with mung bean producers. A total of 39 farms were randomly selected from farms with dominant preceding crops (wheat, barley, and canola) using Cochran's formula. Nevertheless, the relatively small sample size may limit statistical power and generalisability. Farms with other preceding crops were excluded because they are not prevalent in the region and were not the focus of this study. The questionnaire recorded information such as crop yield, type and quantity of inputs (seed, chemical and organic fertilisers, fuel consumption, and labour hours). Farmers were also asked about the crop cultivated in the previous season in order to examine the effect of the "previous crop" on environmental and economic indicators. In the study area, mung beans are mainly cultivated after wheat, barley, and canola; therefore, the data were categorised and analysed based on the preceding crop. (Table 1 presents the average input consumption for each group.)

Table 1- Inputs used per hectare for mung bean production in three crop systems

Input	Unit	Preceding crop		
		Wheat	Barley	Canola
Seed	kg	24.9	25	25.1
Labour	h	71.4	80	80
Fuel	L	67	70.5	78
Electricity	kWh	8.75	0.00	0.00
Fertiliser (manure)	kg	939.4	1000	1000
Fertiliser (N)	kg	45.5	50	50
Fertiliser (P)	kg	45.5	50	25
Fertiliser (K)	kg	16.1	10	25

Ecological Footprint Assessment

To evaluate environmental sustainability, the *FarSo* framework was applied (Blasi *et al.*, 2016). This method organises data within an integrated structure that enables the assessment of the environmental impacts of agricultural activities. In this approach, both the environmental effects of farmers' choices regarding inputs and farm management (measured through the Ecological Footprint Index, EF) and the land's biocapacity in response to management practices (measured through the Biocapacity Index, BC) are considered. The final outputs are the Ecological Footprint (EF) and the Ecological Balance (EB) indices, which together reflect the level of sustainability.

The ecological footprint consists of two components: the input effect (EF_{inp}) and the overproduction effect (EF_{ovp}):

$$EF = EF_{inp} + EF_{ovp} \tag{1}$$

The EF_{inp} index represents the environmental effects resulting from the use of materials and energy during the production process. It relates to using production inputs and is primarily assessed through greenhouse gas emissions (e.g. from fuel, fertilisers, pesticides, electricity, etc.). The EF_{inp} is calculated as the weighted sum of the share of each input:

$$EF_{inp} = \sum_{i=1}^{n} (Q_i \times F_i) \tag{2}$$

where n= total number of inputs, Q_i= quantity of input i used (in appropriate units such as kg, L, h, tonne), F_i= ecological footprint coefficient of input i, expressed in global hectares (gha), representing the environmental impact of producing that input (in gha equivalent of CO_2 emissions and land use).

For inputs whose coefficients were reported in CO_2-equivalent emissions, F_i was calculated as:

$$F_i = e_i \times EQC \tag{3}$$

where e_i is the CO_2-equivalent emission factor per unit of input, and EQC is the conversion coefficient that translates CO_2 emissions into global hectares. In this study, the EQF value was considered 0.35 gha per tonne of CO_2, as proposed by Pomè, Tagliaro, and Ciaramella (2021). The CO_2-equivalent emission factors and ecological footprint coefficients of the inputs are provided in the appendix.

The EF_{ovp} component accounts for the effect of production exceeding the baseline level. First, the minimum attainable yield (Y_{min}) was determined, and then the overproduction coefficient (α) was calculated as follows:

$$\alpha = \frac{Y - Y_{min}}{Y} \tag{4}$$

where Y_{min} is the baseline production level, representing the minimum yield achievable with the lowest external input use (based on field research in the study area, the organic mung bean yield was 200 kg ha^{-1}). Y is the actual crop yield (tonnes ha^{-1}). The α coefficient thus indicates the share of yield directly derived from additional external inputs beyond the minimum level—the larger the α, the greater the dependency on external inputs for yield increases.

The biocapacity (BC), representing the land's regenerative ability, was calculated using the following equation (Wackernagel & Rees, 1998):

$$BC = \left(\frac{Y}{Y_w} \times A\right) \times EQF \tag{5}$$

where Y= average regional yield (tonnes ha^{-1}), Yw = global average yield of the same crop (tonnes ha^{-1}), A= cultivated area (ha), EQF= equivalence factor used to convert hectares to global hectares (gha).

According to the latest reports, the global average annual yield of mung beans is estimated at 730 kg ha^{-1} (World Vegetable Center, 2023).

The Ecological Balance (EB) was then determined as the difference between biocapacity and ecological footprint:

$$EB = BC - EF \tag{6}$$

If EB > 0, the production system has a biocapacity surplus (sustainable). Conversely, if EB < 0, the agricultural activity consumes resources beyond the land's biocapacity (unsustainable).

The Ecological Footprint Index (EFI) is a measure for assessing environmental pressures and evaluating the impacts of agricultural activities on the environment. This index indicates the percentage difference between ecological resilience capacity and the ecological footprint, thus reflecting the sustainability level of a cropping system. Equation (7) is used to calculate the EFI (Liu, Wang, Yang, Zhou, & Liu, 2017). The interpretation of the EFI and its relationship with sustainability levels is presented in Table 2 (Liu *et al.*, 2017). In terms of sustainability, the performance of a system is classified into four categories, and each level is interpreted using a numerical code from 1 to 4.

$$EFI = \frac{BC - EF}{BC} \quad (7)$$

Table 2– Classification of Ecological Footprint Index (EFI) values and corresponding sustainability levels

Level	EFI	Sustainability Level
1	$0.5 < EFI < 1$	Strong sustainability
2	$0 < EFI \leq 0.5$	Weak sustainability
3	$-1 < EFI < 0$	Unsustainable
4	$EFI \leq -1$	Strong unsustainability

Economic Assessment

Alongside the ecological analyses, the economic evaluation also holds great importance, as true sustainability in agriculture requires harmony between environmental and economic dimensions. To examine the economic aspect, a cost-benefit analysis was conducted.

The gross revenue (R) was calculated by multiplying the yield and the selling price of the product:

$$R = Price \times Yield \quad (8)$$

The total cost (TC) included the sum of expenses related to inputs, machinery, labour, and other variable and fixed costs, obtained by multiplying the quantity of each input by its unit price:

$$TC = \sum_{i=1}^{n} (Q_i \times Price_i) \quad (9)$$

To compare the economic performance among different management patterns, two key economic indicators were calculated: Gross Margin (GM) and Benefit–Cost Ratio (BCR), using the following equations:

$$GM = R - TC \quad (10)$$

$$BCR = \frac{R - TC}{TC} \quad (11)$$

where GM: Gross Margin (USD ha^{-1}), R: Gross Revenue (USD ha^{-1}), TC: Total Cost (USD ha^{-1}), BCR: Benefit–Cost Ratio (dimensionless).

The Gross Margin indicates the absolute profit or loss per hectare during the study period, while the Benefit–Cost Ratio reflects the return on revenue relative to costs. Values of BCR>1 denote economic profitability, whereas values of BCR<1 indicate insufficient income to cover production costs.

All prices were reported in a consistent monetary unit (USD per hectare), based on the 2023 price reference year.

Composite index for simultaneous assessment of economic and ecological performance

To determine the optimal preceding crop for mung beans based on both economic profitability and ecological sustainability, a composite index was used. This method involves two main steps: normalisation and aggregation.

Normalisation

Since the selected indicators (benefit–cost ratio (BCR) and ecological footprint intensity index (EFI)) have different ranges, each indicator was first normalised to a scale of 0–1 using the min-max method. For both indicators, a higher value is more desirable. The normalisation formula (Equation 11) is as follows:

$$Score_i = \frac{X_i - X_{min}}{X_{max} - X_{min}} \quad (12)$$

where X_i is the raw value of the indicator for the i-th preceding crop, and X_{min} and X_{max} are the minimum and maximum values of that indicator across the three preceding crops, respectively.

The economic score (Econ) and the ecological score (Ecol) are calculated by placing the raw values of BCR and EFI, respectively, into Equation (11).

Aggregation

The composite index combines the two main dimensions (ecological efficiency and economic profitability) as a weighted average of the two normalised scores:

$$CI = w \times Ecol + (1 - w) \times Econ \quad (13)$$

In this equation, w is the weight assigned to the ecological score (EFI), ranging from 0 (full economic priority) to 1 (full ecological priority).

The index ranges from 0 (worst performance in both criteria) to 1 (best performance in both criteria). A crop rotation with a higher composite index is considered to have a better trade-off between economic profitability and ecological sustainability.

Statistical Analysis

Due to the unequal sample sizes and the violation of normality and homogeneity of variance assumptions, non-parametric and distribution-robust methods were employed to reduce the sensitivity of results to data distribution and outliers. First, the Kruskal–Wallis test was applied to examine the overall differences among the three groups, and the corresponding p-value was estimated. When a significant overall difference was detected, pairwise comparisons were conducted using the two-tailed Mann–Whitney U test to identify the source of variation.

All statistical analyses were performed using IBM SPSS Statistics version 27. Statistical significance was primarily evaluated at the conventional two-tailed level of $\alpha = 0.05$. In addition, results with $0.05 \leq p < 0.10$ were reported as marginally significant, considering the inherent heterogeneity among farms (e.g. differences in soil type, management practices, rainfall, and local climatic conditions) and the exploratory nature of farm-level field data.

Results and Discussion

Statistical analysis of crop rotation effects on ecological and economic indicators

Given the unequal sample sizes and non-normal data distributions, the effect of the preceding crop on ecological (ecological footprint, biocapacity, and ecological balance) and economic (gross revenue and benefit–cost ratio) indicators was examined using the non-parametric Kruskal–Wallis test and pairwise Mann–Whitney comparisons (Table 3). Overall results showed that the preceding crop significantly affected many indicators; in particular, the preceding canola crop differed significantly from wheat and barley. By contrast, differences between wheat and barley were not significant for all indicators, suggesting a relative similarity in the effect of these two crops on the eco-economic sustainability of mung bean cultivation.

The ecological balance index exhibited lower sensitivity to the preceding crop, and differences among groups were not significant. This may indicate the presence of feedback mechanisms in the studied farming systems that—despite changes in ecological footprint and biocapacity—ultimately lead to a relatively similar level of ecological balance. From a management standpoint, this relative stability is important because it implies that some changes in ecological parameters can occur without fundamentally altering the system’s overall balance.

The findings also indicate that the choice of the preceding crops can influence both the environmental pressures and the economic returns of the following crop; therefore, designing crop rotations should be based on a simultaneous assessment of environmental and economic indicators.

Table 3- Impact of preceding crops on ecological and economic indicators of mung-bean production: Statistical analyses of Kruskal–Wallis (overall differences) and Mann–Whitney U (pairwise comparisons)

Index Group	Indicator	Kruskal– Wallis Test	Mann–Whitney U test		
			Wheat vs Canola	Wheat vs Barley	Canola vs Barley
Ecological Indices	Yield	**	**	ns	**
	Ecological footprint	**	*	ns	*
	Biocapacity	**	*	ns	*
	Ecological balance	ns	ns	ns	ns
Economic Indices	Gross margin	**	*	ns	*
	Benefit-Cost Ratio	**	*	ns	*

In the statistical tables, an asterisk (*) indicates $p < 0.10$, two asterisks (**) indicate $p < 0.05$, and ns denotes non-significance.

Effect of the preceding crop on mung-bean yield

The results of this study showed that farms with wheat as the preceding crop produced the highest mung-bean grain yields, while those following canola produced the lowest (means ≈ 664 and 450 kg ha^{-1}, respectively). These findings are consistent with reports by Aynehband and Aghasizadeh (2007), Pourmoeini (2008), and Pourmaeini, Dorfard, Mosayeb Khuzani, and Askari (2011).

One plausible mechanism explaining the yield differences is that preceding-crop residues may influence soil properties and the growing environment of the subsequent crop (Orzech, Wanic, & Załuski, 2025; Pourmaeini *et al.*, 2011). For instance, previous studies have reported that wheat may release phosphorus more rapidly than canola residues, which could be particularly important during the early growth stages of mung beans (Aynehband & Aghasizadeh, 2007). Based on the findings of Aynehband and Aghasizadeh (2007), the relatively higher quality and faster decomposition of wheat residues may promote earlier nutrient release, particularly phosphorus, potentially creating more favourable conditions for mung-bean germination and root establishment. In contrast, although canola may produce a larger volume of residues, its slower decomposition has been reported to result in a more gradual accumulation of organic matter and nutrients, which may delay nutrient availability to subsequent crops. Therefore, consistent with the literature (Aynehband & Aghasizadeh, 2007; Orzech *et al.*, 2025), differences in soil fertility, organic matter accumulation, and nutrient availability could represent some of the factors contributing to the higher mung-bean yields observed after wheat.

Beyond nutrient-release effects, previous studies have suggested that the preceding crop can influence soil biological properties, including soil microbial composition and activity, carbon and nitrogen cycling, and micronutrient dynamics (Schoenau & Campbell, 1996; Yang *et al.*, 2024). These processes may affect nutrient availability to the following crop through changes in carbon: nitrogen ratios, organic matter mineralisation patterns, or decomposer communities. However, because these variables were not measured in the present study, their contribution to the observed yield differences cannot be directly evaluated.

Overall, evidence from this study demonstrates differences in mung-bean yield among preceding-crop categories. The mechanisms discussed above draw on findings from previous research (Aynehband & Aghasizadeh, 2007; Orzech *et al.*, 2025; Schoenau & Campbell, 1996; Yang *et al.*, 2024) and suggest that residue quality, nutrient-release patterns, and soil biological properties may potentially contribute to such differences. Nevertheless, further studies involving direct measurements of soil nutrients, residue decomposition, micronutrient availability, and microbial community dynamics are needed to verify these mechanisms and better explain the processes underlying the observed yield patterns.

Assessment of Environmental Pressure

Table 4 reports the ecological footprint attributable to input use in mung-bean production (per hectare), categorised by preceding crops (wheat, barley, and canola). The EF_{inp} values for mung beans following wheat, barley, and canola were 0.185, 0.202, and 0.199 gha ha^{-1}, respectively. Although the ecological footprint from inputs for mung beans after wheat is somewhat lower than after the other two preceding crops, the Kruskal–Wallis test indicated no significant difference in input-driven ecological footprint among groups (see Appendix Table A2). This implies that, regardless of the preceding crop, the overall environmental pressure arising from input consumption in mung-bean cultivation was relatively similar. By contrast, Table A2 shows that the total ecological footprint, which includes overexploitation, differs significantly among rotations.

Table 4- Ecological footprint of mung bean production inputs based on preceding crops

Input	Preceding crop		
	Wheat	Barley	Canola
Labour	0.036	0.040	0.040
Fuel	0.083	0.092	0.092
Electricity	0.003	0.000	0.000
Fertiliser (manure)	0.003	0.003	0.003
Chemical	0.061	0.066	0.067
EF_{inp}	0.185	0.202	0.199

Ecological Footprint Composition of Input Use

Figure 1 illustrates the share of the input-derived ecological footprint (EF_{inp}) for producing one hectare of mung beans under agricultural systems where wheat, barley, and canola served as the preceding crops. As shown, in all systems, fuel consumption accounts for the largest portion, approximately 45% of the total ecological footprint of mung-bean production. This dominance stems from the heavy dependence of industrial agriculture on fossil fuels.

Following fuel, chemical fertilisers, particularly nitrogen fertilisers (N), represent the second major contributor—around 33% of the total footprint. Nitrogen fertilisers emit nitrous oxide (N_2O) during their production and use, a greenhouse gas with a very high global warming potential, thereby considerably increasing the greenhouse gas emissions of agricultural systems (Millar, Doll, and Robertson 2014). These results underscore the importance of smart fertiliser management and reducing reliance on synthetic fertilisers—for example, by adopting biofertilizers and improving nitrogen-use efficiency. Likewise, the adoption of cleaner fuels or biofuels for agricultural operations is recommended. Such measures not only reduce the ecological footprint but also strengthen the long-term sustainability of agroecosystems.

In the study area, about 4% of the total ecological footprint of mung-bean production was attributed to irrigation operations. Because most irrigation pumps are diesel-powered, the ecological footprint share of electricity use was relatively small. However, a comparison of the ecological footprint per hectare between electric and diesel irrigation systems revealed that electric pumps had a higher ecological footprint. This finding is consistent with the results of Namdari (2025), who compared the environmental impacts of diesel and electric irrigation systems in Iran. According to Namdari’s study, the higher footprint of electric irrigation systems in Iran is largely due to the fossil-fuel-based composition of the national electricity grid.

In other words, although using electric pumps may reduce on-farm emissions**,** indirect

CO_2 emissions from electricity generation, given that much of Iran's electricity is produced from fossil fuels, lead to a greater overall environmental burden compared to diesel-based systems.

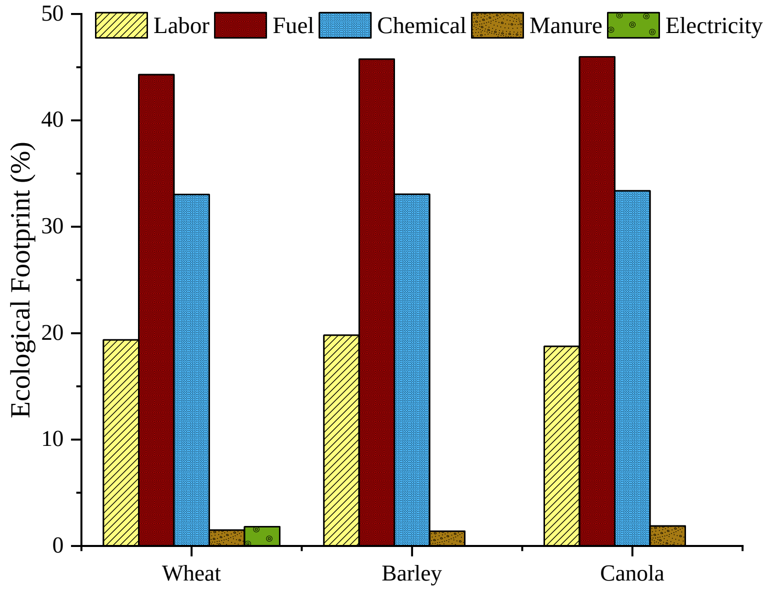

Fig. 1. Contribution of mung bean production inputs to the ecological footprint.

Beyond the composition of the input-driven footprint, the efficiency with which these inputs are converted into yield also differed markedly among rotations. Input use efficiency was assessed as the input-driven ecological footprint per unit of mung bean yield (EF_{inp} $tonne^{-1}$). The wheat–mung bean rotation had the highest input use efficiency, with EF_{inp} of 0.279 gha $tonne^{-1}$, followed by the barley–mung bean rotation (0.311 gha $tonne^{-1}$). The canola–mung bean rotation showed the lowest efficiency (0.442 gha ton^{-1}). In other words, producing one tonne of mung beans required 0.279 gha of input-driven footprint after wheat, whereas after canola this value was 0.442 gha.

Overexploitation Footprint (EF_{ovp})

The EF_{ovp} index (overexploitation footprint), representing the pressure exerted on biocapacity through the use of natural resources, was calculated for mung-bean production following wheat**,** barley, and canola, yielding values of approximately 1.590, 1.541, and 0.856 gha ha^{-1}, respectively. These results indicate that with wheat as the preceding crop, the pressure on the ecosystem's biological capacity (i.e. soil bio-productivity and natural resources) is higher, mainly due to the higher mung-bean yield obtained in this rotation. In other words, the greater crop yield places a higher demand for biocapacity, unless input use efficiency increases proportionally.

A comparison of EF_{inp} and EF_{ovp} (Table 5) shows that the footprint from resource overexploitation (EF_{ovp}) was greater than the input-consumption footprint (EF_{inp}) across all three cropping systems, meaning that overall ecological pressure surpasses local biocapacity potential**.** The EF_{ovp}/EF_{inp} ratio – which indicates whether overexploitation or input consumption dominates – ranged from 4.30 (canola as preceding crop) to 8.59 (wheat as the preceding crop), showing that overexploitation exceeds input consumption by a factor of 4 to 8. In Blasi *et al.* (2016), however, the same ratio ranged from 0.00 to 0.29, meaning that input consumption is the dominant component and overexploitation is negligible. This striking difference (0.00–0.29 in Italy vs. 4.30–8.59 in this study) demonstrates that in Italian systems, overexploitation pressure is less than one-third of input-consumption pressure, whereas in our systems overexploitation dominates by a factor of 4 to 8.

In Blasi *et al.* (2016), EF_{inp} was the prevailing component, and EF_{ovp} was minimal – implying that local biocapacity is sufficient to absorb input-driven pressures without being depleted. In contrast, in Iranian mung-bean systems (this study), the very high EF_{ovp}/EF_{inp} ratios indicate a drawdown of biocapacity via overexploitation. This suggests that yield crops are achieved at the expense of biocapacity loss rather than through efficiency improvements–a pattern unlikely to be sustainable in the long term. Such findings highlight the critical importance of maintaining and enhancing ecosystem biocapacity, as sustainability cannot be achieved merely by reducing input use if the system's regenerative capacity remains weak.

Therefore, reducing EF_{ovp} relative to EF_{inp} requires not merely increasing yield, but ensuring that biocapacity regeneration (e.g. via organic inputs, perennial cover, or diverse rotations) keeps pace with resource extraction. In mung-bean systems, even the best preceding crop (canola) yielded an EF_{ovp}/EF_{inp} ratio of 4.30–still far above the Italian benchmarks–indicating substantial room for improving soil regenerative capacity.

Total Ecological Footprint (EF)

The total ecological footprint (EF), representing the combined environmental pressure from both resource exploitation and input use, was estimated at 1.777 gha ha^{-1} for mung bean following wheat, 1.743 gha ha^{-1} after barley, and 1.055 gha ha^{-1} after canola. Accordingly, mung-bean cultivation after wheat exhibited the highest EF, while that following canola had the lowest. If the objective is to reduce EF without severely compromising income, management strategies that retain the productivity benefits of wheat-based rotations while lowering EF, such as precision fertilisation or conservation tillage, should be adopted.

Biocapacity (BC)

The biocapacity index (BC), which measures an area's ability to produce biological resources and absorb waste, was also computed. The results revealed that mung bean after wheat had the highest biocapacity (2.275 gha ha^{-1}), followed by barley (2.226 gha ha^{-1}) and canola (1.541 gha ha^{-1}).

This clearly indicates that when wheat is used as the preceding crop, mung-bean systems demonstrate greater biocapacity and, consequently, provide more ecological services compared with systems following canola or barley.

Numerous empirical and review studies support this observation, showing that diverse crop rotations enhance multiple soil biological functions and foster richer microbial communities—factors that can indirectly increase biocapacity (Li *et al.*, 2023). The higher biocapacity observed after wheat likely results from improved soil fertility, increased organic matter, and enhanced nutrient availability due to wheat residue incorporation. These findings highlight the role of wheat as a key preceding crop for improving soil properties and strengthening ecological functions in sustainable agriculture.

Ecological Balance (EB)

The ecological balance (EB) index, representing the surplus or deficit of natural resources associated with a particular cropping system, was positive for all three systems, ranging from 0.482 to 0.500 gha ha^{-1}. This indicates that in each system, the biological production capacity exceeded the ecological pressure exerted, meaning that the studied agricultural systems utilised natural resources efficiently and were capable of generating more bio-productive capacity than they consumed. Such results reflect generally sustainable environmental performance across the mung-bean cropping systems evaluated.

Table 5- The effect of the preceding crop on the ecological indicators of mung bean production

Preceding crop	Y	EF_{inp} (gha ha^{-1})	EF_{ovp} (gha ha^{-1})	EF (gha ha^{-1})	BC (gh ha^{-1})	EB (gha ha^{-1})	EFI
Wheat	0.664	0.185	1.592	1.777	2.277	0.500	0.219
Barley	0.650	0.202	1.541	1.743	2.226	0.482	0.216
Canola	0.450	0.199	0.856	1.055	1.541	0.486	0.315

Ecological Footprint Index (EFI)

The Ecological Footprint Index (EFI) measures human demand for natural resources, which leads to climate change, biodiversity loss, soil degradation, and environmental pollution. Based on the calculated EFI values (Table 5), the canola–mung bean rotation, with a value of 0.315, has the highest ecological footprint intensity index and ranks first. Thereafter, the wheat–mung bean rotation, with a value of 0.219, ranks second, and the barley–mung bean rotation, with a value of 0.216, ranks third.

As can be seen, all EFI values fall within the range $0 < EFI \leq 0.5$. According to the standard EFI classification (see Table 2), this range is categorised as "Weak Sustainability". This means that, although in all three systems biocapacity (BC) exceeds the ecological footprint (EF) (EB > 0) and the systems operate within the ecologically sustainable range, the surplus of biocapacity relative to the total capacity is less than 50%. In other words, about 70–80% of the biocapacity of each rotation is consumed by agricultural activities, and the safety margin for sustainability is not large. From an environmental management perspective, this situation is considered acceptable but in need of improvement.

At first glance, the result that canola has the highest relative ecological efficiency (EFI = 0.315) may be surprising, because in the EB (Ecological Balance) index reported in Section 3.3.5, mung bean after wheat had the highest value (0.500 gha ha^{-1}) and mung bean after Barley had the lowest (0.482 gha ha^{-1}). However, in terms of EFI, mung bean after canola ranks first. The reason for this apparent contradiction lies in the formula EFI = EB/BC. Mung bean after canola has a lower biocapacity (BC = 1.541 gha ha^{-1}) compared to wheat (2.277) and barley (2.226) as preceding crops, but its footprint is also much lower (1.055 vs. 1.777 and 1.743). Consequently, the EB/BC ratio for mung beans after canola becomes higher. In other words, although canola as a preceding crop has a smaller absolute surplus, it exerts less pressure per unit of its biocapacity and retains a larger percentage of its capacity (about 31.5% surplus relative to its capacity).

In terms of relative ecological efficiency (pressure intensity per unit capacity), mung beans after canola perform better. This means that if the policy objective is to minimise pressure per unit of available biocapacity, then mung bean after canola is the superior option.

These results show that although mung bean after wheat is superior in terms of absolute balance (EB), mung bean after canola performs better in terms of relative ecological efficiency (surplus-to-biocapacity ratio) and exerts the least pressure per unit of biocapacity.

In summary, the values of the environmental indices highlight the importance of selecting appropriate crop rotations in sustainable agricultural planning. The findings show that different crop rotations can significantly alter the environmental performance of the production system, emphasising the need for integrated decision-making that considers both productivity and ecological sustainability.

Economic Evaluation

To assess the economic performance of mung-bean production under three cropping systems (following wheat, barley, and canola), gross revenue, total cost, gross margin, and benefit–cost ratio (BCR) were calculated per hectare (Table 6).

Production costs were relatively similar across the three systems, ranging from (USD 663 to 698 ha^{-1}) because the main input rates (seed, nitrogen fertiliser, fuel, and labour) were applied uniformly regardless of the preceding crop. Consequently, differences in profitability were driven primarily by revenue rather than by costs.

The highest revenue was obtained in the wheat–mung bean rotation (USD 2,531 ha^{-1}), followed by barley–mung beans (USD 2,476 ha^{-1}), and the lowest in the canola–mung bean rotation (USD 1,714 ha^{-1}). The same pattern was observed for gross margin and BCR: the highest values were recorded for mung beans following wheat (USD 1,887 ha^{-1} and BCR = 2.844), and the lowest for mung beans following canola (USD 1,032 ha^{-1} and BCR = 1.479). Thus, the economic returns closely followed mung bean yield, with cereal-based rotations (wheat and barley) showing a clear economic advantage over the canola rotation. Replacing canola with wheat or barley as the preceding crop increased the gross margin by approximately 80% (from USD 1,032 to USD 1,887 ha^{-1}).

All three rotations were economically viable (BCR > 1). However, the substantially higher BCR values for the wheat- and barley-based rotations indicate considerably greater returns on investment. From a farmer's perspective, a BCR of 2.844 (wheat–mung bean) means that each dollar invested returns USD 2.84, whereas the canola–mung bean rotation returns only USD 1.48 per dollar invested.

Table 6- The effect of the preceding crop on the economic performance of mung bean production

Economic indicator	Unit	Preceding crop		
		Wheat	Barley	Canola
Revenue	($ ha^{-1})	2531	2476	1714
Total Costs	($ ha^{-1})	663	692	698
Gross margin	($ ha^{-1})	1887	1804	1032
Benefit-Cost Ratio	−	2.844	2.608	1.479

Trade-off analysis: selecting the optimal preceding crop for mung bean

To answer which cropping system provides the best balance between ecological footprint reduction and profitability enhancement, a composite index was calculated using the economic score (normalised BCR) and the ecological score (normalised EFI), as described in the Materials and Methods section.

Figure 2 presents the composite index (CI) values for three preceding crops, wheat, barley, and canola, under different weighting scenarios, ranging from full ecological priority to full economic priority.

For the wheat–mung bean rotation, the CI increases from 0.34 (under full ecological priority) to 0.52 (under full economic priority). This indicates that as the weight shifts towards economic priority (increasing the weight of Econ), wheat performs better. The reason is its high economic score (Econ = 0.52) compared to the other two rotations.

For the canola–mung bean rotation, the trend is the opposite. The CI decreases sharply from 0.64 (under full ecological priority) to 0.14 (under full economic priority). This strong decrease reflects the ecological superiority of canola (Ecol = 0.64) and its severe economic weakness (Econ = 0.14). In scenarios with strong environmental emphasis, canola is the best option; however, as the priority shifts towards profitability, it rapidly loses its position.

For the barley–mung bean rotation, the CI values remain intermediate and relatively stable across all scenarios (from 0.27 to 0.47). Barley never ranks first in any scenario, but it acts as a "conservative" and "intermediate" option, showing moderate performance in both dimensions.

The key finding from the figure is the identification of the equilibrium point, or the threshold shift, between the wheat and canola rotations. Under the equal-weight scenario (0.5 Ecol + 0.5 Econ), wheat (0.433) is higher than canola (0.394). Under scenario 0.6 Ecol + 0.4 Econ, canola (0.444) surpasses wheat (0.415).

Consequently, the priority shift threshold occurs at approximately w ≈ 0.55. In other words, if the weight assigned to the ecological score (w) is greater than 0.55, canola is the superior choice; if w is less than 0.55, wheat is the best option. At the equilibrium point (equal or near-equal weights), wheat has a slight advantage, but both are practically acceptable. Barley never crosses this threshold and always remains second or third.

The composite index clearly shows that no single rotation is superior in all scenarios. The optimal choice depends on the decision-maker's priority. Wheat is recommended for economic goals, canola for ecological goals, and barley as an intermediate option. This finding provides a transparent, evidence-based decision-making framework for farmers, agricultural planners, and environmental policymakers.

Given that Golestan Province has a relatively good biocapacity (e.g. wheat BC = 2.277 gha ha^{-1}), the main recommendation of this study is to promote wheat–mung bean rotation, unless in specific areas with severe biocapacity constraints, where canola could be an attractive alternative.

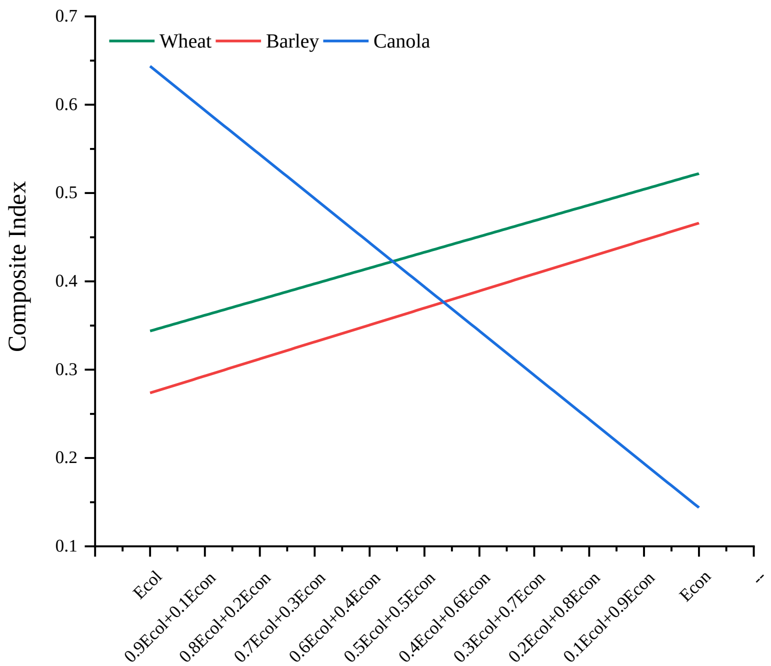

Fig. 2. Trade-off comparison for preceding crops (wheat, barley, and canola) in mung bean cultivation; Ecol = normalised ecological score; Econ = normalised economic score

Conclusion

This study provides an empirical framework using a composite index to simultaneously assess the economic and environmental trade-off in mung bean production under different preceding crops. The results showed that the wheat–mung bean rotation is the most profitable and has the highest biocapacity, but also generates the highest ecological footprint. In contrast, the canola–mung bean rotation has the lowest footprint and the highest relative ecological efficiency, while its profitability is considerably lower. The priority shift threshold at a weight of approximately 0.55 for the ecological index indicates that the optimal rotation choice depends on the policymaker's priorities. Although all rotations exhibit a positive ecological balance (indicating relative sustainability), the footprint intensity index places all of them in the "weak sustainability" category, and the high EF_{ovp}/EF_{inp} ratio reflects strong pressure on biocapacity. Fuel and nitrogen fertiliser use were identified as the main drivers of the ecological footprint.

From a practical perspective, farmers should prioritise wheat as the preceding crop for mung beans to maximise profit and biocapacity, while policymakers should target fuel and nitrogen fertiliser use and replace subsidy schemes that encourage overconsumption with support for low-input or precision farming. Limitations of the study include the sample being restricted to one province and the effect of input subsidies on the underestimation of the true footprint and overestimation of economic performance. Therefore, future research should extend the geographical scope, apply shadow prices to correct subsidy-induced distortions, include social indicators (farmers' acceptance), and track changes in soil carbon and microbial communities over several years.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Fatemeh Nadi: Supervision, Conceptualisation, Methodology, Data pre- and post-processing, Statistical analysis, Software services, Validation, Visualisation, Review and Editing services

Mohamad Hadi Movahednejad: Technical advice, Review and Editing services

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Table A1- CO_2-equivalent emission factors and ecological footprint coefficients of inputs used in mung bean production (Blasi *et al.*, 2016; Pomè *et al.*, 2021)

Input	Unit	Coefficient
Labour	h	0.0005 gha h^{-1}
Fuel	L	0.0032 tonCO_2 kg^{-1}
Electricity	kWh	0.000343 tonCO_2 kWh^{-1}
Fertiliser (manure)	ton	0.008 tonCO_2 ton^{-1}
Fertiliser (N)	kg	3.75 kgCO_2 kg^{-1}
Fertiliser (P)	kg	0.065 kgCO_2 kg^{-1}
Fertiliser (K)	kg	0.037 kgCO_2 kg^{-1}

Table A2– Impact of preceding crop on ecological footprint components: Statistical results for EF_{in} (input-driven), EF_{ovp} (overexploitation), and EF (total) – Kruskal–Wallis and Mann–Whitney U tests

Indicator	Kruskal– Wallis Test	Mann–Whitney U test		
		Wheat vs Canola	Wheat vs Barley	Canola vs Barley
EF_{in}	ns	ns	ns	ns
EF_{ovp}	**	**	*	*
EF	**	*	ns	*

In the statistical tables an asterisk (*) indicates **p** < 0.10, two asterisks (**) indicate **p** < 0.05, and **ns** denotes non-significance

ارزیابی توازن اقتصادی–زیست‌محیطی در تناوب‌های زراعی: مطالعه موردی تولید ماش

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چکیده

ردپای اکولوژیک، میزان فشار انسان بر منابع طبیعی و ظرفیت زیستی محیط را نشان می‌دهد و به‌طور گسترده برای ارزیابی پایداری کشاورزی مورد استفاده قرار می‌گیرد. این پژوهش اثر محصول پیشین (گندم، جو و کلزا) را بر عملکرد زیست‌محیطی و اقتصادی تولید ماش بررسی کرد. داده‌ها از طریق پرسشنامه و مصاحبه با کشاورزان جمع‌آوری شد. شاخص‌های زیست‌محیطی شامل ردپای اکولوژیک (EF)، ظرفیت زیستی (BC) و تراز اکولوژیک (EB)، و شاخص‌های اقتصادی شامل حاشیه سود ناخالص و نسبت فایده به هزینه (BCR) محاسبه شدند. نتایج نشان داد که محصول پیشین تأثیر معنی‌داری بر بیشتر شاخص‌ها داشت ($P<0.05$)؛ به‌طوری‌که کلزا با گندم و جو تفاوت معنی‌دار داشت، در حالی‌که بین گندم و جو تفاوت معنی‌داری مشاهده نشد. از دیدگاه زیست‌محیطی، کشت ماش پس از کلزا کمترین ردپای اکولوژیک کل (۱/۰۵۵ هکتار جهانی در هکتار) و بیشترین کارایی نسبی اکولوژیک (۰/۳۱۵) را داشت، اما کمترین ظرفیت زیستی (۱/۵۴۱ هکتار جهانی در هکتار) را نشان داد. کشت ماش پس از گندم بیشترین ردپای اکولوژیک (۱/۷۷۷ هکتار جهانی در هکتار) و همچنین بیشترین ظرفیت زیستی (۲/۲۷۷ هکتار جهانی در هکتار) را به خود اختصاص داد. اگرچه تراز اکولوژیک در تمامی تناوب‌ها مثبت بود (۰/۴۸۲ تا ۰/۵۰۰ هکتار جهانی در هکتار)، شاخص ردپای اکولوژیک (EFI) در محدوده «پایداری ضعیف» (۰/۲۱۶ تا ۰/۳۱۵) قرار گرفت و نسبت ردپای ناشی از بهره‌برداری بیش‌ازحد به ردپای ناشی از نهاده‌ها (EF_{ovp}/EF_{inp}) بین ۴/۳۰ تا ۸/۵۹ متغیر بود که نشان می‌دهد فشار ناشی از بهره‌برداری بیش‌ازحد به‌مراتب بیشتر از فشار ناشی از مصرف نهاده‌ها است. از نظر اقتصادی، گندم بالاترین حاشیه سود ناخالص (۱۸۸۷ دلار در هکتار) و نسبت فایده به هزینه (۲/۸۴۴) را به خود اختصاص داد، در حالی‌که کلزا کمترین مقادیر را نشان داد (به‌ترتیب ۱۰۳۲ دلار در هکتار و ۱/۴۷۹). شاخص ترکیبی با وزن‌های قابل‌تنظیم زیست‌محیطی–اقتصادی، آستانه مبادله‌ای را در حدود $w \approx 0.55$ نشان داد؛ به‌گونه‌ای که در شرایط اولویت زیست‌محیطی، کلزا و در شرایط اولویت اقتصادی، گندم گزینه برتر بود. با توجه به ظرفیت زیستی منطقه مورد مطالعه، انتخاب گندم به‌عنوان محصول پیشین، متعادل‌ترین ترکیب مدیریت ردپای اکولوژیک و سودآوری اقتصادی را برای تولید ماش فراهم می‌کند.

واژه‌های کلیدی: تحلیل هزینه–فایده کشاورزی، ردپای اکولوژیک، ظرفیت زیستی، کارایی اقتصادی، محصول پیشین

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