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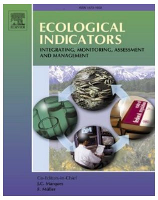

Original Articles

Energy-water-food security nexus in mung bean production in Iran: An LCA approach

J. Abad-González [a,*], F. Nadi [b], D. Pérez-Neira [a]

[a] Department of Economics and Statistics, University of León, Campus de Vegazana s/n, León 24071, Spain
[b] Food science and technology research center of East Golestan, Azadshahr branch, Islamic Azad university, Azadshahr, Iran

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ABSTRACT

Mung bean is a very important crop in Iran in both socio-economic and nutritional terms. However, although discussions on food and food security increasingly include sustainability issues, there are no precedents in academic literature that analyze in depth the nexus between energy, water use and food security in relation to this crop in Iran from an agri-food system approach. Therefore, our main objective is to assess the energy-water-food security (EWFs) nexus and the environmental impact of mung bean production in Iran from a “cradle to fork” approach using different nutritional units (1 kg of beans, 1 kg of proteins, and 1000 kcal) and load allocation criteria. In addition, an economic analysis of the farms is carried out. The results show that the on-farm production of mung beans is the phase where the largest environmental impacts are concentrated (between 40 % and 96 % of them, including those related to water and energy use), while cooking accounts for more than 50 % of the carbon footprint. The non-renewable cumulative energy demand (NR CED) and total water footprint (TWF) per kilogram of beans (“cradle to fork”) is estimated at 27.4 MJ and 1.55 m^3 and the farm Net Margin (NM) is estimated at 3,677 USD per ha. The paper discusses whether mung bean is a low-impact option for protein production, especially when compared to animal products and the importance of using different functional units and load allocation criteria to address the issue of EWFs and sustainability. In this regard, further research is needed to improve the environmental efficiency of bean production, which is critical for promoting sustainable diets in line with food security goals.

1. Introduction

Discussions on food and food security have increasingly taken into account aspects of sustainability, prioritizing low-carbon food patterns that balance healthy and environmentally sustainable diets (McLaren et al., 2021; Aidoo et al., 2023). In this context, the link between energy and water use in food production is a key issue (Mahlknecht et al., 2020; Nkiaka et al., 2021). For this reason, the theorical framework of energy-water-food security (EWFs) nexus is employed to analyze the interrelationship between energy and water use in food production (Putra et al., 2020). The dependence between these dimensions is clear: energy and water are needed to grow and produce food, while food transports energy and water; at the same time, water is needed to obtain energy, and energy is required to transport and irrigate crop fields. One of the most widely used methodologies to address and analyze the EWFs nexus is Life Cycle Assessment (LCA). LCA allows understanding the interactions within the nexus and its feedbacks with other impact categories (such as climate change, acidification, etc.) using an agri-food system approach (Al-Ansari et al., 2015; McAuliffe et al., 2020). Despite the recognition and potentiality of LCA to study this nexus, empirical analyses of specific agrarian products are not abundant. For example, Salmoral and Yan (2018) estimated virtual water and embodied energy in food consumption in the Tamar catchment (England) and Litskas et al. (2019) evaluated the environmental performance of organic and conventional medicinal plant production in the Mediterranean. More recently, Fernández-Ríos et al. (2022) evaluate the energy-water nexus for potato chips, while Armengot et al. (2021) or Del Borghi et al. (2022) do so for four cocoa and horticultural production systems in Bolivia and Mexico, respectively.

Currently, the potentialities and limits of integrating the environmental and nutritional dimension within LCA are being discussed (Ridoutt et al. 2021; McLaren, 2021). From a food security and LCA approach, there is a fundamental problem related to the selection of the functional units of analysis in which studies are developed and comparisons are established (Weindl et al., 2020; Green et al., 2020).

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* Corresponding author.
E-mail addresses: julio.abad@unileon.es (J. Abad-González), dpern@unileon.es (D. Pérez-Neira).

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Main acronyms

Acronyms and Definition

AC	Acidification
CED	Cumulative energy demand
CF	Carbon footprint
EEr	Economic efficiency ratio
EI of NM	Energy intensity of net margin
EROI	Energy return of investment
EROWI	Energy return of water investment
ET	Ecotoxicity
EU (FW)	Eutrophication (freshwater)
EU (M)	Eutrophication (Marine)
EU (T)	Eutrophication (Terrestrial)
EWFs nexus	Energy-water-food security nexus
HT	Human toxicity
IR	Ionizing radiation
LCA	Life-cycle assessment
LF	Land footprint
NM	Net margin
NR CED	Non-renewable cumulative energy demand
NR EI	Non-renewable energy intensity
NR EROI	Non-renewable EROI
OD	Ozone depletion
PM	Particulate matter
PO	Photochemical ozone formation
RU	Resource use
TC	Total cost
TWF	Total water footprint
WF	Water footprint

Although some research has been done using energy and/or protein as functional units to assess the environmental impact of different animal and plant products (Doran-Browne et al., 2015, Xu et al., 2018), mass and volume are the most common functional units (Pérez-Neira et al., 2023), even though they do not capture all food functions, including the nutritional function (Bianchi et al., 2020; Avadí et al., 2021). Thus, when compared on a mass basis, animal products have greater impacts (including water footprint) than plant products (Mekonnen and Gerbens-Leenes, 2020; Svanes et al., 2022), although this difference decreases when evaluated in terms of the amount of protein produced (Sonesson et al., 2017; Boch-Ibsen et al., 2022). Furthermore, researchers have stressed the importance of incorporating a comprehensive nutritional analysis of food, including amino acids (McAuliffe et al., 2022), as well as more complete nutritional indices (Bianchi et al., 2020; Simón et al., 2023) to offer more precise dietary recommendations.

Consequently, further research is needed on eco-efficiency indicators with a nutritional approach (nutritional-LCA) to assess impacts (energy-water, emissions, etc.) in relation to different functional units (energy, protein, or other nutrients, etc.) allowing a more comprehensive view on food and diets (Skaf et al., 2021). This is particularly important in the case of legumes since they are the second most important food source after cereals (FAOSTAT, 2023). In fact, 70 % of plant protein consumed by humans is provided by cereals and legumes, but due to the low amount of protein in the former (9 % to 12 %) and its high content in the latter (18 % to 32 %), developing countries have drawn attention to these crops. Additionally, legumes are a good source of carbohydrates, dietary fiber, vitamins, minerals, and phenolic compounds, including phenolic acids, flavonoids, and lignin, which are considered to have a positive effect on human health (Lin and Lai, 2006). In this sense, pulses play an important role in ensuring the overall well-being and food security of small and marginalized farmers by meeting the protein needs of their diet (Singh, 2017). Economically speaking, beans are also the second largest source of agricultural products and account for 36.5 % of the world food production (Statista, 2017).

In this regard, some works have used the LCA methodology to analyze the energy metabolism and/or carbon footprint (CF) emissions of legumes productions (lentils, beans, chickpeas, etc.) in different parts of the world, i.e.: Iran (Kazemi et al., 2015; Elhami et al., 2017; Nadi, 2023); India (Patil et al., 2014) or Italy (Del Borghi et al., 2022) (Table S1, included in the supplementary materials). Some of these works have also evaluated the economic dimension of the crop (Moraditochaee et al., 2014; Patil et al., 2014) because profitability is a key aspect in technical-production decision-making (Caicedo-Vargas et al., 2023). Other studies have compared the environmental repercussions of different management systems, with a focus on organic management (Asakereh et al., 2010; Abeliotis et al., 2013). As regards to the life cycle of the crop, Ilari et al. (2019) estimated various environmental impact categories associated with the production and processing of 1 kg of frozen green beans in Italy while Heusala et al. (2020) or Svanes et al. (2022) assessed the impacts associated with producing 1 kg of protein (coming from various plant and animal products) using a "cradle to farm gate" approach for Europe and Norway, respectively. Bandekar et al. (2022) included cooking and showed that this phase has the highest impact in terms of emissions, energy use and water consumption and Tidåker et al. (2021) pointed out the importance of transportation in energy use and greenhouse gas emissions, especially when pulses are packaged and cooked for final consumption. More recently, Aidoo et al. (2023) and Yasuf (2023) compared (in terms of mass and protein) the impact of producing different products based on vegetable protein (meatballs, bacon) with their meat counterparts.

However, studies evaluating the entire life cycle, including the "cooking phase," and introducing functional units that link environmental impact and nutritional quality are rare and none of them delve into the economic dimension during the farm stage. (Table S1). This research aims to fill this gap in the scientific literature. Consequently, our primary objective is to analyze the EWFs nexus and environmental impact of bean production from a "cradle to fork" approach using various nutritional units (1 kg of beans, 1 kg of proteins and 1000 kcal) and different load allocation criteria. The secondary objective is to conduct an economic analysis of the crop at the farm stage to assess its profitability. Specifically, we chose the mung bean in Iran as a case study. Mung bean (*Vigna Radiata [L.] R. Wilczek*) is a tropical and subtropical legume whose worldwide cultivation area constitutes approximately 7.3 million hectares, yielding an annual harvest of over 5.3 million tonnes (Nair and Schreinemachers, 2020). In Iran, 1.4 % of the cultivated area is devoted to bean production, with 14 % of this area (FAOESTAT 2023) being mung bean (25,000 ha) (Farhoudi and Hamze, 2018). In addition to nutritional issues, this crop is agronomically interesting because it provides fodder, green manure and contributes to soil fertility (Kazemi et al., 2016). Thus, this plant not only stabilizes atmospheric nitrogen, but also enriches the soil with nitrogen and prepares the ground for successful cultivation (Huňady and Hochman, 2014). This ability to biologically stabilize nitrogen, together with the short growing period and the production of highly digestible and silage-friendly forage, are some of the interesting advantages of mung beans for entering crop rotation in different regions of the world, particularly, in Iran (Majnoun-Hoseini, 2008). Based on the collection of primary information at different stages of the product life cycle in Iran, the European environmental footprint methodology (Zampori and Pant, 2019) and cost-benefit analysis (farm stage) were used.

This study is novel in several aspects. First, it is the first study that evaluates the environmental impact of the mung bean agri-food system in Iran based on the nutritional profile of the food. Second, it is one of the few studies that assesses the whole life cycle of mung bean including the "cooking phase" and introduces functional units that link environmental impact and nutritional quality. Lastly, it is the first study that integrates the economic dimension at the farm stage in the LCA of mung bean. Despite the limitations highlighted in section 4.3, this study of the Energy-Water-Food security nexus using nutritional LCA and additional economic-environmental indicators provides scientifically rigorous insights for policy makers, technicians, and/or managers seeking to promote new approaches to crop production and healthy, environmentally sustainable diets.

2. Materials and methods

2.1. Case study and data collection

The region of study is the Iranian province of Golestan (N 36°-30́-38°-8́; E 53°-57́-56°–22́). Plowing of mung bean is done in autumn or winter. In early spring, a disk harrow is used to remove weeds, add manure to the soil and prepare the land for herbicides, which are applied with the disk harrow before sowing the seeds. Planting is done from mid- to late spring and, after germination, the disk harrow is used to remove weeds and improve soil aeration, making the soil warmer and retaining moisture. Irrigation begins in June and ends in mid- or late August, depending its frequency on the type of soil and the ambient temperature. All water pumps operate on electricity. Harvesting is done from mid- to late September or early October. Once the beans are cropped, they are packed in plastic bags and distributed, mostly for local consumption.

Data were collected from a sample of mung bean farmers in the province of Golestan using a "face-to-face" questionnaire. After a previous technical and production-related characterization, 25 farms were selected to obtain a non-random representation of the different types of management, being preferably selected those providing reliable information and implementing a good system of production management. The questionnaire asked about the crop yield as well as the inputs used in the production, e.g., fertilizers and farmyard manure, human labor and diesel fuel. The information gathered allowed us to carry out the LCA of the product. Additionally, the average distance traveled per kg of mung beans and the amount of plastic used for its packaging were estimated. Since consumption of this product is mainly local, the travelled distance does not usually exceed 180–220 km and they are transported in medium-sized trucks. The beans are marketed, as mentioned above, in a plastic bag (0.025 [±0.005] kg). Finally, an average mung beans cooking time (40 min [±5]) using a conventional pot and natural gas was also considered.

2.2. Environmental and economic impact assessment based on life cycle analysis methodology

2.2.1. System boundaries and functional units

We present the analyses using two approaches: first we focus on the impacts at the bean production stage ("cradle to farm gate" approach) and then we complete the analyses by including the other stages of the agri-food system ("cradle to fork" or "cradle to plate" approach). Additionally, two criteria were used to assign environmental loads. Firstly, an economic criterion was used since straw has no commercial value in our study, all environmental loads were allocated to mung bean production. Secondly, a mass criterion was used where the environmental impact was distributed according to mung bean and straw production measured in kg. In addition to the hectare, the functional units used, for the economic analysis and the territorial footprint were three: 1 kg of beans, 1 kg of proteins, and 1,000 kcal. For reasons of space, only the indicators referred to 1 kg of beans and 1 kg of proteins, following an allocation of economic loads, are presented throughout the text while the remaining estimates are shown in Table S2, included in the supplementary materials.

2.2.2. Energy-water-food security nexus at the farm production stage ("cradle to farm gate" approach)

First of all, to estimate the amount of land required to produce a functional unit of product (1 kg of beans or 1 kg of proteins), the land footprint (LF) was calculated (Eq. (1)). Secondly, the energy output (EO) was calculated as the sum of MJ in the beans and straw (Eq. (2)). On the input side, the cumulative energy demand (CED) measures both the on-farm use of energy (direct energy) and the indirect energy required for the production of inputs and capital goods used in production management (Eq. (3)). A distinction was made between renewable (R CED) and non-renewable (NR CED) energy use (Eq. (4)). The total water footprint (TWF) was defined as the water footprint of irrigation plus the sum of the water footprints of the inputs used in the production process (Eq. (5)). The coefficients required to calculate the energy output were taken from Moreiras (2005), while the CED and the WF were estimated by implementing the Environmental Footprint 3.0 methodology version 1.02 (Zampori and Pant, 2019), and analyzing the Ecoinvent 3.5 database with SimaPro software.

$$\mathrm{LF} = \mathrm{Y}_{(\mathrm{b})}^{-1} \tag{1}$$

$$\mathrm{EO} = \mathrm{Y}_{(\mathrm{b})} \times \alpha_{(\mathrm{b})} + \mathrm{Y}_{(\mathrm{s})} \times \alpha_{(\mathrm{s})} \tag{2}$$

$$\mathrm{CED} = \sum \mathrm{I}_{(\mathrm{j})} \times ß_{(\mathrm{j})} \tag{3}$$

$$\mathrm{NR\ CED} = \mathrm{CED} - \mathrm{R\ CED} \tag{4}$$

$$\mathrm{TWF} = \mathrm{WF}_{\mathrm{irrigation}} + \mathrm{WF}_{\mathrm{inputs}} \tag{5}$$

Where LF = Land footprint; $\mathrm{Y}_{(\mathrm{b})}$ = Bean yield (kg/ha); EO = Energy output (MJ/ha); $\alpha_{(\mathrm{b})}$ = Energy coefficient of beans (MJ/kg); $\mathrm{Y}_{(\mathrm{s})}$ = Straw yield (kg/ha); $\alpha_{(\mathrm{s})}$ = Energy coefficient of straw (MJ/kg); CED = Cumulative energy demand (MJ/kg); $\mathrm{I}_{(\mathrm{j})}$ = Input *j* (fertilizers, energy, crop protection, tools, etc.) (unit/kg); $ß_{(\mathrm{j})}$ = Energy coefficient of input *j* (MJ/unit); NR CED = Non-renewable cumulative energy demand (MJ/kg); R CED = Renewable cumulative energy demand (MJ/kg); TWF = Total water footprint (m^3/kg); $\mathrm{WF}_{\mathrm{irrigation}}$ = Water footprint of irrigation (m^3/kg); $\mathrm{WF}_{\mathrm{inputs}}$ = Water footprint of inputs (fertilizers, diesel, machinery, etc.) (m^3/kg).

The energy return on investment (EROI) measures the energy efficiency of agricultural systems, especially in relation to the use of non-renewable energy (NR EROI) (Eq. (6)), while the non-renewable energy intensity (NR EI) measures the production (kg of beans or protein per ha) by MJ of non-renewable energy (Eq. (7)). Finally, the EROWI (energy return on water investment) measures the efficiency of the interrelationship between energy output and water use (Eq. (8)).

$$\mathrm{EROI\ or\ NR\ EROI} = \mathrm{EO} \times (\mathrm{CED\ or\ NR\ CED})^{-1} \tag{6}$$

$$\mathrm{NR\ EI} = \mathrm{Y}_{(\mathrm{b}+\mathrm{s})} \times \mathrm{NR\ CED}^{-1} \tag{7}$$

$$\mathrm{EROWI} = \mathrm{EO} \times \mathrm{TWF}^{-1} \tag{8}$$

2.2.2.1. Economic efficiency. To investigate the economic dimension, a cost-benefit analysis of the farms was carried out. That is, the income (I) and total costs (TC) of the different inputs were estimated, as well as their net margin (NM) (Eq. (9)). Additionally, the economic efficiency ratio (EEr) (Eq. (10)) and the energy intensity of the net margin (EI of NM) (Eq. (11)), which measure the relationship between revenues and expenses, and between NM and energy use, respectively, were also calculated.

$$\mathrm{NM} = \mathrm{I} - \mathrm{TC} \tag{9}$$

$$\mathrm{EEr} = \mathrm{I} \times \mathrm{TC}^{-1} \tag{10}$$

$$\mathrm{EI\ of\ NM} = \mathrm{NM} \times \mathrm{NR\ CED}^{-1} \tag{11}$$

Where NM = Net margin (USD/ha); I = Income (USD/ha); TC =

Total cost (USD/ha); EEr = Economic efficiency ratio; EI of NM = Energy intensity of NM (USD/MJ).

2.2.3. Impact assessment of the mung bean agri-food system

Besides these analyses, thirteen additional impact categories were estimated: global warming potential, i.e., carbon footprint (CF); ozone depletion (OD); ionizing radiation (IR); photochemical ozone formation (PO); particulate matter (PM); cancer- and non-cancer-related human toxicity (HT); acidification (AC); freshwater (FW), marine (M) and terrestrial (T) eutrophication (EU); ecotoxicity (ET), particularly freshwater (FW); and resource use (minerals and metals) (RU) (Eq. (12)). These impact categories, together with CED and TWF, were calculated from both "cradle to farm gate" and "cradle to fork" approaches, by means of the afore-mentioned environmental footprint methodology.

$$\mathrm{Impact}_{(i)} = \sum \mathrm{Input}_{(j)} \times \Omega_{\ (i,\ j)} \tag{12}$$

$\mathrm{Impact}_{(i)}$ = Environmental impact *i* (where *i*: carbon footprint, ozone depletion, etc.) (unit/kg); $\mathrm{Input}_{(j)}$ = Input *j* (where *j*: fertilizers, machinery, transport, packaging, electricity, etc.) (unit/kg); $\Omega_{\ (i,j)}$ = Characterization factor of impact *i* in relation to input *j*, which allows aggregating and homogenizing the releases (impact/unit).

2.3. Statistical and sensitivity analysis

When using the "cradle to farm gate" approach, bootstrapping was used to estimate confidence intervals for the means of the indicators since not all the observed variables are normally distributed. Bootstrapping is a statistical procedure that resamples a single data set with replacement to create many simulated samples, allowing the calculation of standard errors or confidence intervals that are asymptotically more accurate than the standard intervals obtained using the sample variance and the assumption of normality (DiCiccio and Efron, 1996). Specifically, the percentile bootstrap (Efron and Tibshirani, 1993) is the chosen method to construct the 95 % confidence intervals from the distribution of 2,000 replications of the mean as the estimator (see Figs. S1 and S2, included in the supplementary materials). To obtain the "cradle to fork" estimates, a combination of bootstrapping (for the production stage) and simulation (for the other three stages) was used. Specifically, for each indicator, stage, and replication, 25 random numbers (the sample size) were simulated from the corresponding symmetric triangular distributions whose parameters were obtained from the afore mentioned bounds (180–220 km, for transport; 0.020–0.030 kg, for packaging; and 35–45 min, for cooking). For each replication (i) and indicator (j), the mean of the random numbers corresponding to transport (t), packaging (p), and cooking (c) were added to the bootstrap sample of the corresponding production indicator (x^B), thus obtaining a point estimate of the mean value of the indicator under a "cradle to fork" approach ($\bar{y}^B$) (see Eq. (13)). Then, the 2,000 replications of this procedure allowed us to obtain simulated distributions of each indicator and estimates of the 95 % confidence intervals of their means using percentiles (see Fig. S3, included in the supplementary materials). All analyses were performed using R statistical software v.4.2.1 and the following packages: tidyverse (v.1.3.2), infer (v.1.0.3), and EnvStats (v.2.7.0).

$$\bar{y}^B_{ij} = \frac{1}{25}\sum_{k=1}^{25}\left(x^B_{ijk} + t_{ijk} + p_{ijk} + c_{ijk}\right) \tag{13}$$

3. Results

3.1. Energy-water-food security nexus and economic efficiency in mung bean production ("cradle to farm gate" approach)

Table 1
EWFs nexus of mung bean farm production. Means and 95% bootstrap confidence intervals.

Particulars	Unit	Bean	95 % CI	Bean protein	95 % CI
1. Food production					
Land footprint	ha/t	1.60	[1.46–1.77]	6.89	[6.30–7.62]
2. Energy					
CED	MJ/kg	20.7	[18.9–22.7]	89.7	[81.8–98.3]
NR CED	MJ/kg	14.1	[12.7–15.5]	60.7	[54.8–67.2]
3. Water					
TWF	m3/kg	1.47	[1.33–1.62]	6.36	[5.74–6.96]
4. Energy and water efficiency					
EROI	–	0.77	[0.71–0.84]	–	–
NR EROI	–	1.15	[1.05–1.24]	–	–
NR EI	kg/MJ	0.075	[0.069–0.081]	0.017	[0.016–0.019]
EROWI	MJ/m^3	11.06	[10.0 – 12.1]	–	–

The land footprint associated with the production of 1 tonne of beans was 1.6 ha though, taking protein as reference, the figure increases to 6.90 t/ha (Table 1). As can be seen in Fig. S4, included in the supplementary materials, which shows the energy metabolism of crop production, straw accounted for 33 % of the energy output. The CED per kilogram of beans was estimated at 20.7 MJ; 68 % of which came from non-renewable energy sources, so the NR EROI was estimated at 1.15. This means that for every unit of non-renewable energy invested in mung bean production, only 1.15 units of energy are obtained. Inorganic fertilization, manure use, and diesel were the most important energy items, each accounting for approximately 94 % of the CED (Fig. 1). The TWF of the crop was 1.47 m^3 kg^{-1} of beans. Irrigation accounted for 43.0 % of the TWF. Excluding irrigation, inorganic fertilization was responsible for 89 % of the WF of the inputs. In terms of efficiency, the EROWI showed how, for each cubic meter of water, 11.06 MJ of mung beans were produced. This amount rose to 16.47 MJ when straw was also considered (Table S3). Table 2 shows the profitability and economic efficiency indicators for mung bean production in Iran. Total costs were estimated at 968 USD/ha, while the income and net margin was 4.8 and 3.8 times higher than the total cost. The most important monetary cost was the use of machinery (36 %), followed by irrigation expenses (24 %) and the purchase of seeds (18 %) (Fig. 1). Labor only accounted for 2.5 % of the total expenses. In terms of efficiency, the EEr was estimated at 4.86, while the EI of NM was 0.42 USD/MJ, i.e., a net margin of 0.42 USD was obtained for each unit of non-renewable energy used (NR CED) on the farm.

3.2. Environmental impact of the mung bean supply chain ("cradle to fork" approach)

Table 3 shows all analyzed environmental impact categories of the supply chain for 1 kg of beans. For example, producing, packaging, transporting and cooking 1 kg of mung beans has a CED, CF, and WF of 27.4 MJ, 2.88 kg CO2-eq, and 1.55 m^3 of water, respectively. The farm stage accumulates between 40 % and 95.0 % of all impacts (Fig. 2), particularly in the TWF, OD, IR, and HT (cancer) categories. As seen in Fig. 1, inorganic fertilization is the most important input in all impact categories (between 32 % and 83 %) except for OD and EU, where energy and manure respectively have the largest share. Packaging has a particularly important weight on CED and RU (approx. 9 %). Transportation is the phase with the lowest impact (between 0.0 % and 3.4 %), because mung beans are mostly consumed within short distances.

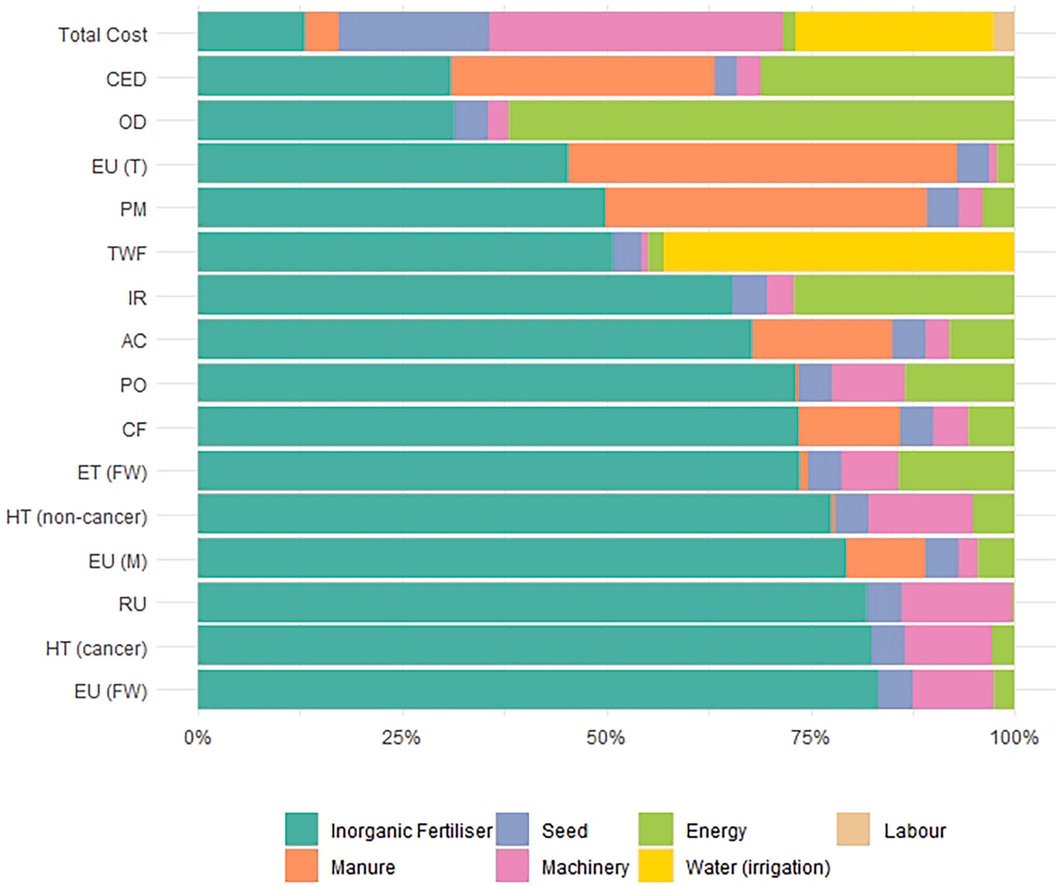

Fig. 1. Structure of the environmental impact of producing, packaging, transporting, and consuming 1 kg of mung beans (%): "cradle to farm" gate approach.

Table 2
Profitability and economic efficiency of mung bean farm production. Mean and 95% bootstrap confidence intervals.

Particulars	Unit	Mean	95 % CI
5. Economic input/output			
TC	USD/ha	968	[913 – 1,021]
Income	USD/ha	4,641	[4,254–5,027]
6. Economic efficiency			
NM	USD/ha	3,677	[3,299–4,029]
EEr	–	4.86	[4.45–5.30]
EI of MN	USD/MJ	0.42	[0.38–0.47]

On the other hand, the mung bean "cooking stage" is considerably impactful (between 0.5 % and 56.0 %), particularly in terms of CF, CED and AC. The amount of impact varies depending on the functional unit used and the environmental load allocation criteria (see 4.2).

4. Discussion

4.1. Energy-water-food security nexus in mung bean production

Efficiency in the use of water and energy when producing food constitutes a fundamental element in the implementation of new agricultural practices and the development of sustainable agri-food systems based on food security (Mahlknecht et al., 2020; Nkiaka et al., 2021). Most studies have analyzed water and energy consumption in agriculture separately, without considering the complex linkages and interactions between them. Few studies have investigated the nexus between energy and water in food. Some examples can be found in Litskas et al. (2019) for medicinal plants, Fernández-Ríos et al. (2022) for potato chips, Armengot et al. (2021) for cocoa, and Del Borghi et al. 2021 for horticultural crops. In our study, the CED of producing 1 kg of mung beans ("cradle to farm gate" approach) is within the range of magnitude of previous studies (between 1.53 and 34.74 MJ/kg) (Moraditochaee et al., 2014; Patil et al., 2014; Nadi, 2023). This wide range is influenced by several variables including legume type, management system and geographic location. For example, Elhami et al. (2017) identified the use of nitrogen fertilizer as the main energy hotspot in lentil production in Iran. Our study further shows that inorganic fertilization is also a hotspot in terms of water footprint. A reduction in fertilizer use or its substitution by biofertilizers can lead to a reduction in water footprint and thus fossil energy use (Wang et al., 2022). In addition, on-farm energy consumption for irrigation and machinery is another important part of the NR CED for mung bean production in Iran. Abeliotis et al. (2013) also pointed out this input as an energy hotspot in lentil production. Better selection of irrigation pumps, installation of drip irrigation (Cui et al., 2022), and further optimization of tillage practices, repair and maintenance of machinery could lead to more efficient use of energy and water (Elhami et al., 2017).

When assessing EWF nexus approach, it is therefore necessary to also consider the WF associated with the production of inputs. Our data show how the WF of inputs can be higher than the WF of irrigation, implying that most of the water use occurs off-farm. The farms analyzed have the capacity to produce 19.40 MJ contained in the beans per m^3 of irrigation, but 11.06 MJ when considering the TWF (EROWI). Armengot et al. (2021) also took TWF into account in their evaluation of different cocoa systems. Bandekar et al. (2022), however, only estimated the water footprint of irrigation of various legumes in the United States. In addition, in a context of globalization, where production and consumption

Table 3
Environmental footprint of mung bean production, packaging, transportation and cooking in Iran (“cradle to fork” approach) (per kg of bean). Mean and 95% bootstrap confidence intervals.

Particulars	Unit per kg	a. Production	b. Transport	c. Packaging	d. Cooking	Total (a + b + c + d)	
						Mean	95 % CI
NR CED	MJ	1.41E + 01	6.25E-01	2.46E + 00	1.03E + 01	2.74E + 01	[2.59E + 01–2.91E + 01]
TWF	m^3	1.47E + 00	0.00E + 00	6.94E-02	7.00E-03	1.55E + 00	[1.41E + 00–1.69E + 00]
CF	kg CO_2 eq	1.14E + 00	4.23E-02	8.57E-02	1.61E + 00	2.88E + 00	[2.71E + 00–3.04E + 00]
OD	kg CFC11 eq	1.67E-07	9.17E-09	3.39E-09	1.27E-13	1.80E-07	[1.64E-07–1.96E-07]
IR	kBq U-235 eq	1.12E-01	2.07E-03	4.41E-03	0.00E + 00	1.18E-01	[1.07E-01–1.31E-01]
PO	kg NMVOC eq	2.92E-03	9.71E-05	3.47E-04	1.10E-03	4.45E-03	[4.16E-03–4.77E-03]
PM	disease inc.	1.02E-07	3.08E-09	3.34E-09	2.25E-08	1.31E-07	[1.21E-07–1.42E-07]
HT (non-cancer)	CTUh	1.66E-08	5.16E-10	7.31E-10	1.79E-09	1.97E-08	[1.78E-08–2.17E-08]
HT (cancer)	CTUh	7.01E-10	1.50E-11	3.34E-11	5.91E-12	7.54E-10	[6.77E-10–8.42E-10]
AC	mol H + eq	9.68E-03	1.33E-04	3.20E-04	3.95E-03	1.41E-02	[1.32E-02–1.51E-02]
EU (FW)	kg P eq	3.00E-04	1.12E-05	2.11E-05	0.00E + 00	3.32E-04	[2.97E-04–3.68E-04]
EU (M)	kg N eq	1.89E-03	2.46E-05	7.06E-05	3.39E-04	2.32E-03	[2.10E-03–2.57E-03]
EU (T)	mol N eq	4.33E-02	2.55E-04	7.19E-04	3.67E-03	4.79E-02	[4.39E-02–5.21E-02]
ET (FW)	CTUe	2.31E + 01	4.06E-01	8.42E-01	4.43E + 00	2.88E + 01	[2.61E + 01–3.17E + 01]
RU	kg Sb eq	1.14E-05	2.75E-08	1.31E-06	0.00E + 00	1.27E-05	[1.16E-05–1.40E-05]

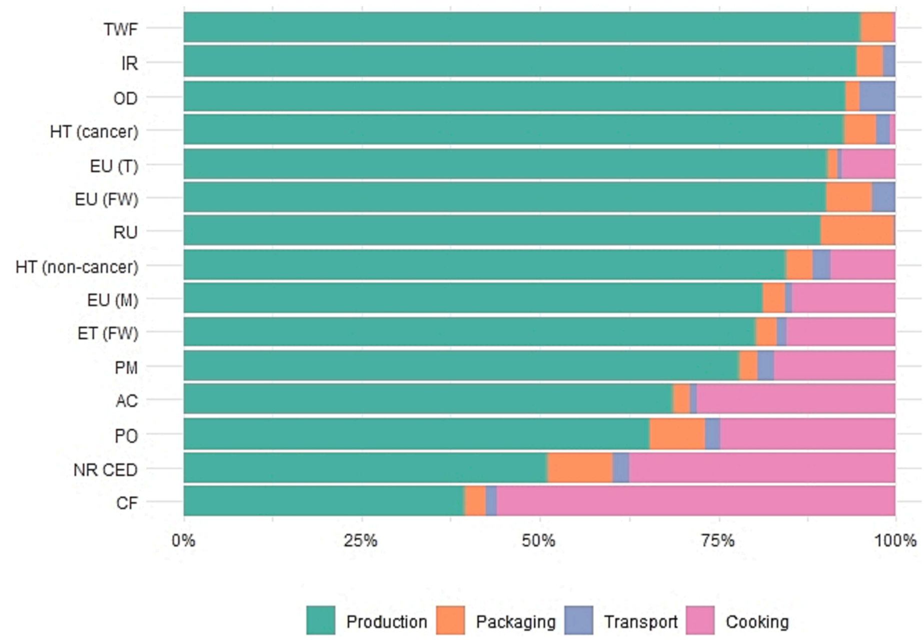

Fig. 2. Structure of the environmental impact of producing, packaging, transporting, and consuming 1 kg of mung beans (%): “cradle to fork” approach.

patterns are increasingly manifested on a global scale, and commodity supply and distribution networks often cross several national and regional borders, the sustainability of the EWFs nexus at farm level is insufficient and an agri-food system approach is needed (Al-Ansari et al., 2015; McAuliffe et al., 2020). Although bean production on Iranian farms is the stage with the highest impact in almost all categories, the packaging, transportation or cooking of beans in Iran cannot be neglected. Similar to this study, Bandekar et al. (2022) highlight cooking for consumption as the most impactful phase for pulses in the USA, accumulating between 75 % and 87 % of the CF, CED or EU mainly due to electricity use. In other words, the consumption of water-energy to meet human nutritional needs occurs along the entire supply chain. Mung beans in Iran have a low-impact packaging and are mostly consumed locally, which explain the lower weight of these two phases. However, as pointed out by Ilari et al. (2019) or Tidåker et al. (2021), long travel distances can contribute significantly to increase the environmental impact of pulses, especially when they are processed, frozen and packaged far from the final destination. This could be the case for exported Iranian beans.

4.2. *Nutricional-LCA and food security*

Most previous studies have focused their analyses on functional units (kg of beans or hectare) (see Table S1) that do not allow capturing all the nutritional functions of foodstuffs (Bianchi et al., 2020; Avadí et al., 2021) and/or do not make visible the energetic importance of the production of non-edible products such as straw (Figure S4). Thus, assessing the environmental impact of producing 1 kg of proteins and/or 1000 kcal of beans allows to understand and compare different nutritional alternatives served on the plate (Doran-Browne et al., 2015; Xu et al., 2018). Plant-based proteins have a lower environmental impact (energy-water, land footprint, etc.) than animal-based proteins, which is why there is currently a debate on the role that pulses should play in sustainable and healthy diets (Mekonnen and Gerbens-Leenes, 2020; Boch-Ibsen et al., 2022). For example, 1 kg of animal protein has a CF between 27 and 197 CO_2-eq, while plant protein has a CF between 1.8 and 8.8 kg CO_2-eq (“cradle to retail” approach) (Weindl et al., 2020). Our results show evidence in this direction. Adapting the limits of our system in order to be able to compare results, the CF of 1 kg of bean proteins would be around 5.05 kg CO_2-eq. This lower impact of legume protein relative to other animal protein sources (Heusala et al., 2020; Svades et al. 2022) also holds for processed foods. For example, Aido et al. (2023) show how the production of soy milk and soy meatballs could offset up to 64–85 % CF compared to cow's milk and veal sausages, while Yasuf (2023) obtains similar results for bacon of vegetable origin. At an aggregate level, Röös et al. (2021) showed how reducing meat consumption (by 50 %) and increasing legume consumption could lead to a 20 % reduction in CF and a 23 % reduction in land use in Sweden. Moreover, in the Iranian case, the higher profit-to-cost ratio of mung beans compared with other strategic products, such as sugar beets (Erdal et al., 2007), soybeans (Mandal et al., 2002), canola (Unakitan et al., 2010), or rice (Kulyakwave et al., 2020), contributes to a higher food security and economic welfare level of smallholder farmers producing that crop.

On the other hand, the debate on the allocation of environmental loads between co-products is key in terms of sustainability and thus food security (Fig. S4). Straw production and reuse, although lacking economic and nutritional value, is important in terms of multifunctionality, biodiversity and management: it serves to feed livestock, which avoids environmental costs, and/or serves as biomass for fertilizing agricultural systems (Pérez-Neira et al., 2018; Zhou et al., 2023). By incorporating these ecological functions into the valuation model and thus distributing the environmental loads according to a non-economic criterion (in our case, mass), the environmental impact of producing 1 kg of beans or protein is reduced. The planning and optimization of food production therefore require metrics and methods that facilitate a quantitative analysis of the trade-offs and synergies between the nutritional, health, economic and environmental dimensions of food security sustainability considering the agri-food system as a whole (McLare et al. 2021; Bianchi et al., 2020). In this sense, as our study shows, nutritional-LCA enriches the assessment of the impact of food production using functional units and/or environmental load allocation criteria that allow a more comprehensive and complex analysis of the nexus between EWFs and sustainability providing meaningful information to support the development of public policies aimed at food security and optimization of agricultural practices (Green, 2020; Skaf et al., 2021).

4.3. Limitations and future research

Finally, we would like to highlight some of the limitations of this research that can constitute future lines of work: a) The analysis has focused on conventional mung bean production in one of the most important producing regions in Iran (Farhoudi and Hamze, 2018). It would be necessary to compare it with the economic and environmental performance of other regions, as well as to analyze it over a longer time period, taking into account the management systems, particularly distinguishing between organic and agroecological (Asakereh et al., 2010; Abeliotis et al., 2013); b) It would also be interesting to evaluate different marketing and packaging alternatives for mung beans, and to pay further attention to cooking techniques in local gastronomy as a cultural link between diet, environmental impact and food security; c) it would be worthwhile evaluating the real potential for CF reduction (the EWFs nexus and other metrics) of a dietary change where beans, including processed plant protein foods (Aido et al. 2023; Yasuf, 2023), replace or complement animal protein to different degrees (Svanes et al., 2022; Röös et al., 2021) according to the current conditions in Iran; and d) It would be appropriate to use other metrics that allow for more complex inclusion of the nutritional role of beans in diets when planning future scenarios and making comparisons between foods (McAuliffe et al., 2022; Ridoutt, 2021).

5. Conclusions

In this research we assessed the energy-water-food security (EWFs) nexus and environmental impact of mung bean production in Iran from both "cradle to farm gate" and "cradle to fork" approaches using different nutritional units and load allocation criteria. The non-renewable cumulative energy demand (NR CED) and total water footprint (TWF) per kilogram of beans ("cradle to fork") is estimated at 27.4 MJ and 1.55 m3 and the farm Net Margin (NM) is estimated at 3,677 USD per ha. The results showed that the farm phase was the main source of environmental impacts (between 40 % and 96 % of all impacts) in the mung bean supply chain, especially those related to water use and cancer-related categories. However, other stages such as packaging, transportation, and cooking also had significant impacts in terms of NR CED or carbon footprint (CF). The functional unit based on protein content reflected the nutritional value of mung bean better than the functional unit based on mass or energy content thus suggesting that mung bean can be a low-impact option for protein production, especially when compared to animal products. Therefore, promoting mung bean consumption could contribute to more sustainable diets and food security in addition to being a locally available and profitable food for farmers. However, more research is needed to improve the environmental efficiency of the mung bean EWFs nexus throughout the supply chain by identifying and implementing best practices for water management, fertilizer use, pest control, packaging design, transportation optimization, and cooking methods, as well as to explore the social and cultural aspects of mung bean production and consumption in Iran and other regions.

CRediT authorship contribution statement

J. Abad-González: Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Funding acquisition. **F. Nadi:** Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing. **D. Pérez-Neira:** Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Appendix A. Supplementary materials

Supplementary materials to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.111442.

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