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Optimization of environmental and energy performance of egg production using data envelopment analysis (DEA) and life cycle assessment (LCA)

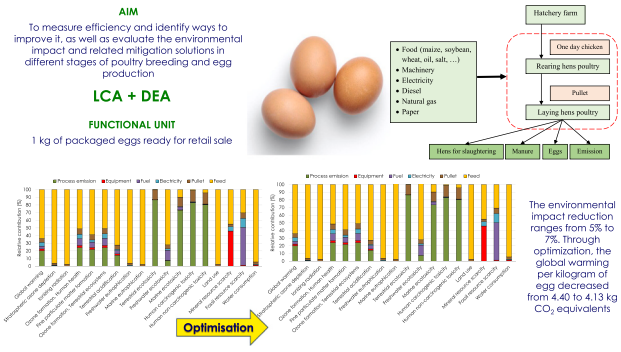
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HIGHLIGHTS

- Environmental and energy performance off egg production were evaluated
- Data envelopment analysis and life cycle assessment were combined
- 14 pullet breeding farms and 40 egg production farms in Iran were considered
- Feed consumption is the main responsible of the environmental impact
- Through optimization global warming (6.1 %) and energy consumption (6.5 %) can be reduced

GRAPHICAL ABSTRACT



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ABSTRACT

Intensive farming systems can present different environmental concerns. Among the many animal products, eggs are consumed globally as a cheap, valuable source of protein. Iran is among the top 10 egg producing countries in the world. However, the environmental impact of egg production in Iran is scarcely investigated.

This study aims to optimize the environmental and energy performance of egg production in Iran. It utilizes the eco-efficiency method, which combines Data Envelopment Analysis (DEA) and Life Cycle Assessment (LCA). To this purpose, data from 14 pullet breeding farms and 40 egg production farms were collected through in-person questionnaires.

The energy performance of egg production is mainly related to the consumption of feed, electricity, and fuel, as well as to the use of equipment. The average energy inputs for pullet breeding and egg production were 270,283.06 MJ (per 1000 pullets) and 1,606,307 MJ (per 1000 laying hens), respectively. Improved management can save 105,190 MJ of energy per 1000 laying hens without compromising output performance. The greatest potential for reducing energy consumption lies in inputs such as fuel and feed. The eco-efficiency method demonstrated that improved management can reduce environmental impact by 5–7 %. Through

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optimization, global warming decreased from 4.40 to 4.13 kg CO_2 equivalents per kg of egg. For the evaluated impact categories, feed input showed the greatest contribution to environmental impact.

Abbreviations

DEA	data envelopment analysis
LCA	life cycle assessment
kg	kilogram
CO_2	carbon dioxide (vol%)
NH_3	ammonia
PM	particulate matter
DMU	decision making units
km^2	square kilo-metre
SEA	saved energy amount
SEP	saved energy percentage
RIE	real input energy
IPCC	Intergovernmental Panel on Climate Change
NO_2	nitrogen oxide
L	liter
m^3	cubic meter
MJ	mega joules
CH_4	methane gas
AoP	areas of protection
FDEA	fuzzy data envelopment analysis
kWh	kilo-watt-hour
CCR	charns, cooper, and rhodes
EMS	efficiency measurement system
FU	functional unit

1. Introduction

With the world's population approaching 8 billion people, the demand for food has increased significantly. This trend of population growth will exert pressure on available resources and the environment (Laca et al., 2021; Kaveh et al., 2020; Jahanbakhshi et al., 2020). The agricultural sector contributes significantly to global warming; to address this issue, we must measure and manage energy in agricultural systems, to properly manage environmental impact and improve energy security (Hesampour et al., 2022a).

Sustainable agriculture should integrate high productivity and minimal environmental impact while feeding the growing world population. Therefore, we must identify the sources of environmental impact and provide solutions to improve energy efficiency and mitigate this impact (Pishgar-Komleh et al., 2020(. In all agricultural systems, it is possible to reduce environmental impact.

In recent decades, there has been increasing consideration of the environmental effects of agricultural products, particularly animal products (Biagetti et al., 2023; Huang et al., 2024; Zoli et al., 2023). Among livestock, the poultry sector shows lower environmental impact than other sectors due to its high feed efficiency. The main environmental concerns in this sector are carbon dioxide (CO_2), ammonia (NH_3), and particulate matter (PM) (Payandeh et al., 2017; Lin et al., 2017; Wood et al., 2015).

In 2021, global egg production reached approximately 1.5 billion tons, with most eggs being produced in Asia. Specifically, China, India, Japan, and Russia are the primary Asian egg producers (Laca et al., 2021). Additionally, Iran produces 1.3 million tons of eggs annually (Shahbandeh, 2024). The international egg commission aims to increase global egg consumption by over 100 % by 2032, with a target of one egg per person per day, or 365 eggs per person per year. This highlights the significance of egg production and consumption, emphasizing the need to address energy and environmental performance in this food sector.

Evaluating food production systems as a significant source of greenhouse gas emissions requires a comprehensive and complete method. The World Business Council for Sustainable Development has introduced the eco-efficiency method to examine and manage various environmental and operational aspects in evaluating sustainable development. The objective of this method is to improve resource efficiency and minimize environmental impact. It combines Data Envelopment Analysis (DEA) and Life Cycle Assessment (LCA) methods to achieve environmental efficiency (Hesampour et al., 2023; Vásquez-Ibarra et al., 2021). The above-mentioned methods are used to identify a set of producing units with the best performance in terms of efficiency and environmental results. The DEA method can be used to find information to help reduce the amount of input to inefficient producing units while maintaining the output level, optimizing resource consumption. The LCA approach focuses on the energy and material flows and quantifies the potential environmental impact.

The DEA + LCA method can be performed in three different ways: the five-step, three-step, and four-step methods. The choice of method depends on the type of variables used in the DEA method (Mohammadi et al., 2015; Najafabadi et al., 2022).

In production systems with multiple similar inputs and outputs, the DEA method is used to measure the relative efficiency of decision-making units (DMUs). DEA is a non-parametric optimization model. The application of DEA allows the most efficient DMUs (i.e., those that produce the highest output in the statistical population using the lowest input) to be identified (Hesampour et al., 2022b; Heidari et al., 2021). LCA is a valuable environmental modeling tool for analyzing complex systems. It evaluates a product's environmental performances throughout its life cycle and identifies mitigation solutions.

In recent years, several studies have focused on the environmental impact of poultry sector (Gržinić et al., 2023; Guo et al., 2024), some specifically on egg production (Costantini et al., 2020; Pelletier, 2017; Ghasempour and Ahmadi, 2016; Maciel et al., 2023; Kheiralipour et al., 2023; Guillaume et al., 2022). However, until now, only two studies have investigated energy consumption and the environmental impact of egg production in Iran using the DEA (Sefeedpari et al., 2012) and LCA (Ghasempour and Ahmadi, 2016) methods.

In this context, this study aims to measure energy efficiency and identify ways to improve it, as well as to evaluate the environmental impact and related mitigation solutions in different stages of poultry breeding and egg production. Currently, no studies combining DEA and LCA have been conducted on optimizing energy consumption and environmental impact in egg production in Iran.

2. Materials and methods

2.1. Study area and data collection

The study was conducted in Isfahan province, Iran, which has a semi-arid climate. This province is situated in central Persia between the massive central Zagros Mountains and the grand desert. It covers an area of approximately 107,027 km^2 between 30° 42′ and 34° 30′ N latitude and 49° 36′ and 55° 32′ E longitude (Fig. 1). Isfahan province has a total of 64 poultry farms, of which 43 are active. Additionally, there are 192



Fig. 1. Geographical map of Isfahan Province, Iran.

egg production farms in the province, of which 124 are active. The province is located at an altitude of 1571 m above sea level and is known for its egg production, ranking first in Iran with a production of 13,344 tons per year.

The data for this study were collected in 2021 and 2022 from 14 pullet breeding farms and 40 egg production farms, through an in-person questionnaire. The questionnaire contained questions regarding inputs and outputs in the pullet breeding and egg production environments. The data collected on the different farms were kept anonymous.

Random sampling was conducted to ensure greater accuracy in data collection and findings, and the sample size was determined using Cochran's technique based on Eq. (1) (Hosseinzadeh-Bandbafha et al., 2017)

$$n = \frac{N(S \times t)^2}{(N-1)d^2 + (S \times t)^2} \quad (1)$$

where n is the required sample size, N is the number of pullet breeding/egg production farms in the target population ($N_{\text{pullet breeding}} = 43$, and $N_{\text{egg production}} = 124$), t is the reliability coefficient ($t = 1.96$, denoting 95 % confidence level), S is the variance of studied qualification in population ($S_{\text{pullet breeding}} = 0.0969$, and $S_{\text{egg production}} = 0.1883$), and d is the permitted error ratio deviation from the average population ($d = 5$ %). The n values (sample sizes) for pullet breeding and egg production farms were 10.80 and 37.86, respectively. To ensure greater accuracy in data collection and findings, the sample sizes (n) for pullet breeding and egg production farms were selected as 14 and 40, respectively.

The Super Nik Jake breed was used in all the farms. The pullet breeding period was 90 days, and the egg-laying period was 546 days. One-day-old chicks entered the pullet breeding farms, where they were raised for 90 days under the necessary conditions. After 90 days, the pullets were removed from the breeding farms and entered the egg production farms as input. This began the 546-day egg-laying period. From 1 to 132 days, no eggs were produced, and the laying hens were given special feed to prepare their bodies to lay eggs. At day 133, egg production was at 5 %; it reached 88 % at day 167. Egg production showed an upward trend and reached its peak, i.e., 96 %, on day 265. After this point, due to physiological conditions such as aging and reduced physical strength of the laying hen, the production of eggs declined. By day 546, egg production reached 80 %.

The pullets were raised in beds in all-pullet breeding farms, while the laying hens were farmed in cages. Most producers (67 %) used pulpit laying hen cages, while the others (33 %) used fully automatic cages. In pulpit laying hen cages, eggs and manure are collected manually, whereas in automatic ones, manure and eggs are collected automatically by belt conveyor. Next, the eggs are sorted and labeled according to the production batch. In the subsequent stage, they are packed and prepared for distribution in the consumer market. The laying hens' manure is transferred to warehouses. At the end of each week, it is loaded onto trucks and removed from the pullet breeding farms. The chickens' average weight at the end of the pullet-raising and egg-laying periods was 1.100 kg and 1.600 kg, respectively.

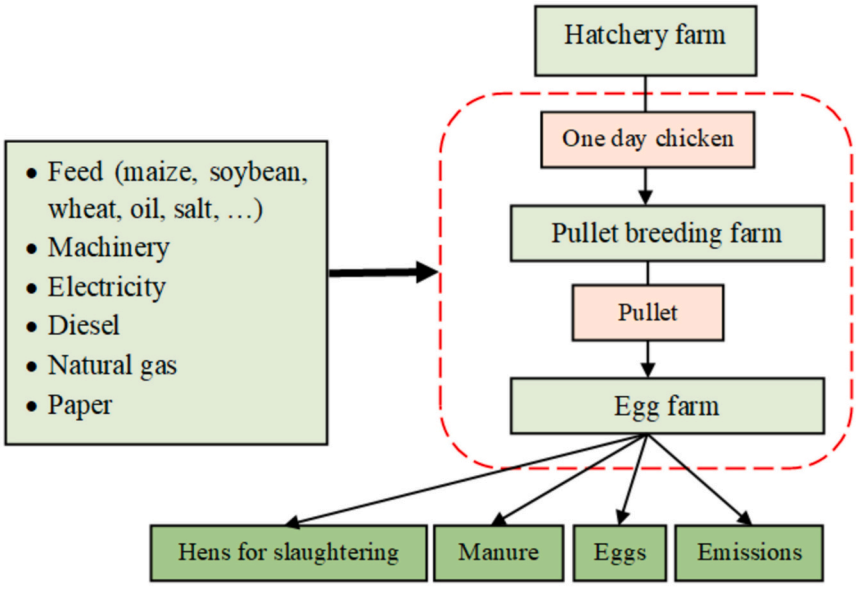


Fig. 2. System boundary for the egg production chain (foreground system within dashed rectangle).

Table 1
Inputs consumed in pullet breeding farms and egg production.

Parameter	Pullet production (90 days)			Egg production (546 days)		
	Minimum	Maximum	Average	Minimum	Maximum	Average
Feed (kg)	70,532	358,010	132,412	537,056	8,603,648	2,556,441
Electricity (kWh)	15,342	89,514	45,861	6905	1,611,253	457,110
Diesel (L)	58,000	120,000	94,400	40,000	300,000	147,875
Natural gas (m^3)	13,043	144,928	54,678	78,261	1,043,478	381,642

2.2. Eco-efficiency

The DEA + LCA method analyzes the flow of energy and materials in breeding and production farms, to improve efficiency and reduce harmful environmental effects. It consists of five steps and calculates environmental criteria directly related to the operational performance of decision-making units (Vázquez-Rowe and Iribarren, 2015). The steps are as follows:

1) Collecting data
2) Investigating the environmental effects using the LCA method
3) Measuring efficiency using the DEA method and determining target values
4) Analyzing environmental effects on target values
5) Comparing the environmental effects on the current target values in Steps 2 and 4.

The primary objective of this approach is to explore solutions for decreasing resource consumption and environmental impact (Andretta et al., 2021).

2.3. DEA

DEA is a non-parametric method used to measure the efficiency of breeding and production farms. It introduces a set of the most efficient farms in the statistical population, which use the fewest inputs, and gives them a score of 1. Other units in the population receive a score of less than 1 and are considered inefficient. DEA brings the inefficient units to the efficiency frontier by providing a set of inputs and outputs to improve their efficiency. DEA models can be either input-oriented or output-oriented. The input-oriented model aims to reduce the amount of input while maintaining the amount of output. In agricultural modeling, the input-oriented model is preferred because it gives producers more control over the number of inputs. The analysis of efficient and inefficient units utilizes the saved energy percentage, which is calculated as follows (Hu and Kao, 2007):

$$SEP = \frac{SEA}{RIE} \times 100 \quad (1)$$

where SEP is saved energy percentage (%), SEA is saved energy amount (MJ/1000 chicken), and RIE is real input energy (MJ/1000 chicken). SEP indicates a reduction in input energy without a decrease in output, making it a valuable indicator of inefficiency. It takes into account the energy saving and consumption of each decision-making unit (Hu and Kao, 2007). The study utilized EMS 1.3 software for analysis and employed the input-oriented CCR model for farm evaluation.

2.4. LCA

This study investigates the egg production chain from pullet breeding. 1 kg of packaged eggs ready for retail sale was selected as a functional unit; for the system boundary (Fig. 2) a "*from cradle to farm gate*" perspective was considered. In detail, the system boundary includes pullet breeding and egg production. Pullet breeding farms produce 90-day-old chicks as output, while egg production farms use pullets as input and produce packaged eggs as output. Pharmaceutical, veterinary, and cleaning products used in production farms were excluded from the system boundary due to the small quantities utilized and the lack of information about their impact.

Table 2
Average values of CH_4 and N_2O in the pullet breeding and egg production periods.

Parameters	Pullet production	Egg production
N_2O indirect (kg N_2O/yr)	7.14009E-05	0.00092
N_2O direct (kg N2O/yr)	0.00092	0.01186
CH_4 (Gg CH_4 /yr)	1.11	24.69

The inventory data were modeled using SimaPro 9.0 software. Background data were retrieved from (i) Ecoinvent database for electricity and equipment inputs, (ii) the US LCI database for fuel (diesel and

Table 3
Average energy inputs and outputs for pullet breeding farms.

Input/Output	Unit	Quantity per 1000 pullets	Energy equivalent (MJ)	Energy value (MJ/1000 pullets)
A. Input	–	–	–	270,283
1. Chicks	kg	42	10.33 (Heidari et al., 2011)	433.86
2. Feed	kg	3705.85	–	36,612
2.1 Maize	kg	2296.93	7.90 (Atilgan and Koknaroglu, 2006)	18,146
2.2 Soybean	kg	971.46	12.60 (Atilgan and Koknaroglu, 2006)	12,240
2.3 Dicalcium phosphate	kg	55.91	10 (Ramedani et al., 2019)	559
2.4 Minerals	kg	51.50	1.59 (Payandeh et al., 2017)	82
2.5 Vitamins	kg	33.77	1.59 (Ramedani et al., 2019)	53.70
2.6 Fatty acid	kg	67.03	37 (Payandeh et al., 2017)	2480.25
2.7 Salt	kg	7.45	1.59 (Ramedani et al., 2019)	11.84
2.8 Wheat	kg	221.80	13.70 (Guillaume et al., 2022)	3038.71
3. Electricity	kWh	1513.90	11.93 (Mousavi-Avval et al., 2011)	18,060.85
4. Fuels	–	–	–	214,981
4.1 Gas	m^3	1690.28	49.50 (Payandeh et al., 2017)	83,669
4.2 Diesel	l	2747.12	47.80 (Elhami et al., 2019)	131,312
5. Equipment	kg	–	–	195.62
5.1 Polyethylene	kg	15.39	46.30 (Kittle,1993)	23.70
5.2 Galvanized iron	kg	80.34	38 (Sefeedpari et al., 2012)	101.76
5.3 Steel	kg	20.18	62.70 (Heidari et al., 2011)	42.19
5.4 Electric motor	kg	12.95	64.80 (Chauhan et al., 2006)	27.97
B. Output	–	–	–	103,167
Pullets	n	933.86	110 (Sefeedpari et al., 2012)	102,724
Poultry Manure	kg	1475.23	0.30 (Kalhor et al., 2016)	442.57

Table 4
Average energy inputs and outputs for egg production farms.

Input/output	Unit	Quantity per 1000 laying hens	Energy equivalent (MJ)	Energy value (MJ/1000 laying hens)
A. Input	–	–	–	1,606,307
1. Pullet	n	1000	110 (Sefeedpari et al., 2012)	110,000
2. Feed	kg	57,894.25	–	529,628
2.1 Maize	kg	33,865.99	7.90 (Atilgan and Koknaroglu, 2006)	267,541
2.2 Soybean	kg	13,788.92	12.60 (Atilgan and Koknaroglu, 2006)	173,740
2.3 Dicalcium phosphate	kg	1017.69	10 (Ramedani et al., 2019)	10,177
2.4 Minerals	kg	4717.91	1.59 (Ramedani et al., 2019)	7501
2.5 Vitamins	kg	549.78	1.59 (Payandeh et al., 2017)	874
2.6 Fatty acid	kg	734.09	37 (Payandeh et al., 2017)	27,161
2.7 Salt	kg	122.17	1.59 (Ramedani et al., 2019)	194.25
2.8 Wheat	kg	3097.69	13.70 (Guillaume et al., 2022)	42,438
3. Electricity	kWh	12,991.75	11.93 (Mousavi-Avval et al., 2011)	154,991
4. Fuels	kg	–	–	798,799
4.1 Gas	m^3	10,635.68	49.50 (Payandeh et al., 2017)	526,466
4.2 Diesel	l	5697.34	47.80 (Elhami et al., 2019)	272,332.97
5. Equipment	kg	–	–	12,888
5.1 Polyethylene	kg	76.13	46.30 (Kittle, 1993)	705
5.2 Galvanized iron	kg	1502.37	38 (Sefeedpari et al., 2012)	11,418
5.3 Steel	kg	30.73	62.70 (Heidari et al., 2011)	385.35
5.4 Electric motor	kg	29.27	64.8 (Heidari et al., 2011)	379.32
B. Output	–	–	–	–
Eggs	kg	19,359.11	7.28 (Baum et al., 2009)	140,934
Manure	kg	22,622.57	0.30 (Kalhor et al., 2016)	6787
Total output	kg	–	–	147,721

gas), and (iii) the Agri-Footprint database for the feed input.

During the inventory analysis, the production farms' inputs and outputs, including consumed resources, energies, and emissions, were quantified. Table 1 presents the main inputs used in pullet breeding and egg production farms.

The primary ingredients in laying hen and pullet feed are maize and soybeans. The feed also contains supplements (0.66 %), oil (1.25 %), salt (0.21 %), baking soda (0.15 %), carbonate (8 %), phosphate (1.81 %), methionine (0.20 %), lysine (0.09 %), troyin (0.03 %), clin (0.04 %), and wheat bran (5 %). The Agri-footprint database was used to assess the environmental impact of feed used before 17 weeks (the pullet breeding stage) and after 17 weeks (the egg production stage).

CH_4 and N_2O are significant emissions in poultry farming and egg production. The emissions of CH_4 and NO_2 were calculated and estimated using the Tier 2 approach and IPCC guidelines. Table 2 presents the average values of CH_4 and N_2O during the pullet breeding and egg production periods.

2.5. Impact assessment

The inventory data were characterized using the characterization factors provided by the ReCiPe Midpoint (H) V1.13 method (Huijbregts et al., 2017). ReCiPe considers midpoint and endpoint levels. The midpoint approach examines environmental impacts from the release of a substance or consumption of a resource.

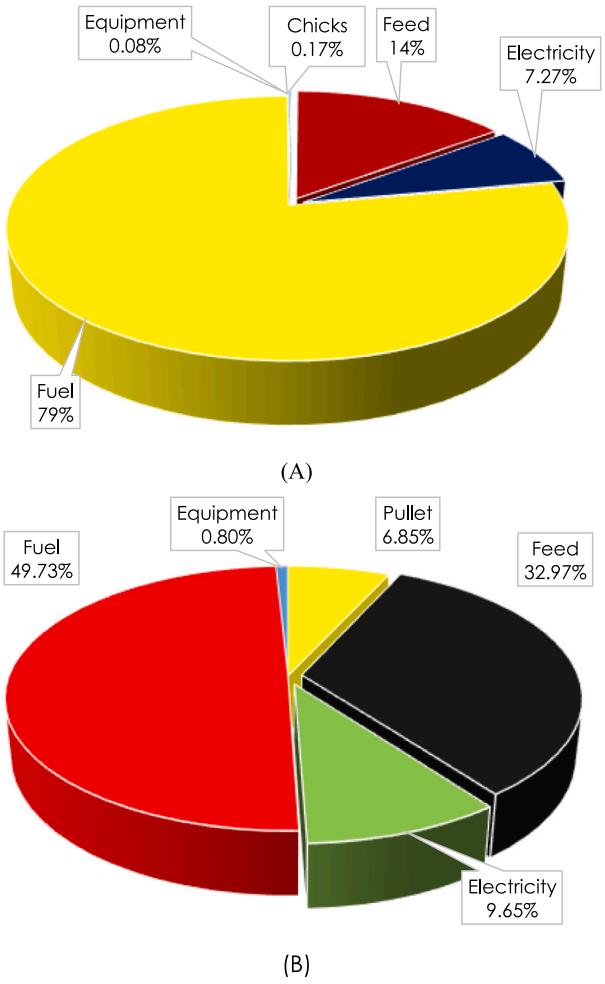


Fig. 3. Energy consumption in pullet breeding (A), and egg production (B).

At midpoint level, the following 18 impact categories were evaluated: climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, marine eutrophication, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, ionizing radiation, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion.

At endpoint level, three areas of protection (damage categories) were considered: human health, ecosystem, and resources (Dong et al., 2021).

3. Results and discussion

3.1. Energy and DEA results

Tables 3 and 4 show the results of energy analysis (inputs and outputs) for pullet breeding and egg production.

During pullet breeding, for every 1000 pullets, an average of 270,283.06 MJ of energy input was used, and the average output energy was 103,167 MJ. On the other hand, during egg production, the energy input and output per 1000 laying hens was 1,606,307 and 147,721.10 MJ, respectively. Sasanya and Olaifa (2022) analyzed energy consumption in poultry management for egg production in Nigeria and reported an average energy input of 122,461.12 MJ per day. Similarly,

Table 5
Current and target energy values in pullet breeding farms.

Input/output	Energy value (MJ/1000 pullets)		SEA (MJ/1000 pullets)	SEP (%)
	RIE	Target		
Input				
1. Chicks	433.86	431.22	2.64	0.61
2. Feed	36,611.54	36,394.43	217.10	0.59
3. Electricity	18,060.85	17,949.44	111.41	0.62
4. Fuels	214,981.19	214,166.21	814.95	0.38
5. Equipment	195.62	194.57	1.055	0.54
Total	270,283.06	269,135.90	1147.13	0.42

Table 6
Current and target energy values in egg production farms.

Input/output	Energy value (MJ/1000 laying hens)		SEA (MJ/1000 laying hens)	SEP (%)
	RIE	Target		
Input				
1. Pullet	110,000	103,749	6251.02	5.68
2. Feed	529,628.30	499,701.70	29,926.57	5.65
3. Electricity	15,4991.60	144,107.50	10,884.10	7.02
4. Fuels	798,799.40	741,455.40	57,344.05	7.18
5. Equipment	12,887.70	12,103.33	784.37	6.09
Total	1,606,307	1,501,117	105,190.10	6.55

Sefeedpari et al. (2012) investigated the energy consumption pattern of poultry in Iran's Rose Egg Farms using Fuzzy Data Envelopment Analysis (FDEA) and reported an average total energy input of 709,759.9 MJ per 1000 chickens.

Fig. 3 shows energy consumption related to pullet breeding and egg production. Feed and fuel, consisting of diesel and gas, represent the largest proportion of energy input.

During pullet breeding and egg production, 214,981.19 MJ (per 1000 pullets) and 798,799.40 MJ (per 1000 laying hens) of energy, respectively, were consumed as fuel, accounting for 79 % and 50 % of the total energy consumption. This input is consumed mainly for heating purposes. The high fuel consumption is related to its affordability, availability, and the dry climate of the region. Improper management and inadequate equipment and facilities increased fuel consumption. In many modern production farms worldwide, the hot air exiting the hall is used to heat the incoming air. Unfortunately, few farms in Iran are equipped with such a heating system. The ventilation flow in most production halls in Iran takes the form of a tunnel, where fresh air enters from one side and exits from the other. The ventilation systems in the halls involve considerable heat dissipation. To reduce fuel consumption, new heating equipment should be installed. This equipment not only reduces fuel consumption but also improves air quality, reducing the occurrence of respiratory diseases. Additionally, insulating the walls and ceiling of the halls is crucial for managing energy consumption on farms. Hall insulation effectively prevents temperature exchange between the interior and exterior air, resulting in reduced heat loss in winter and cooler temperatures in summer (Ghasempour and Ahmadi, 2016; Payandeh et al., 2017). It is important to inform producers about these modern facilities and provide them with governmental support to improve production farm conditions.

Besides fuel, feed is the second most significant contributor to energy consumption, mainly due to the consumption of maize and soybean. In egg production farms, feed input accounts for 33 % of the total energy consumption, while in pullet breeding farms, it accounts for 14 %. Electricity, which is used for lighting and to power feeding devices and water transfer systems, accounts for less than 10 % of the total energy consumption. The equipment used consumes the least energy in both pullet breeding and egg production, accounting for only 1 %.

To optimize energy in the farms studied, the DEA method was applied to determine target energy values. The efficient and inefficient energy units were then analyzed using the ratio of SEP. Table 5 shows that, in the breeding farms, the total amounts of required energy and optimal energy were 270,283.06 and 269,135.90 MJ per 1000 pullets, respectively. The greatest energy savings were achieved with fuel, particularly gas, amounting to 814.95 MJ per 1000 pullets. By taking into account the percentage of energy savings in production farms, it is possible to reduce input energy by 0.38 % without decreasing output levels.

Table 6 presents the required and target energy, SEA, and SEP for egg production farms. The results indicate that energy consumption can be reduced from 1,606,307 to 1,501,117 MJ per 1000 laying hens by optimizing fuel and feed inputs. Specifically, the amount of fuel can be reduced from 798,799.40 to 741,455.40 MJ, resulting in a savings of 57,344.05 MJ of energy consumption at this stage. The target energy for the feed input is 499,701.70 MJ; compared to the current energy consumption, this is an energy saving of 29,926.57 MJ for this input.

Table 7
Current and target input values for pullet breeding and egg production farms.

Input/output	Unit	Pullet breeding farm		Egg production farm	
		Current	Target	Current	Target
Inputs					
1. Chicks	kg	42	41.74	0	0
2. Pullet	bird	0	0	1000	943.17
3. Feed	kg	3705.04	3683.93	57,894.25	54,633.74
4. Electricity	kWh	1513.90	1504.56	12,991.75	12,079.42
5. Fuel	–	–	–	–	–
Gas	m^3	1690.28	1673.81	10,635.68	9827.51
Diesel	L	2747.12	2747.12	5697.34	5334.59
6. Equipment	kg	128.85	128.11	1638.50	1538.65
Outputs					
Pullets	bird	933.85	933.85	0	0
Eggs	kg	0	0	19,359.11	19,359.11
Manure	kg	1475.23	1475.23	22,622.57	22,622.57

3.2. Eco-efficiency

Table 7 presents the input data in both current and target conditions, calculated using the DEA method for pullet breeding and egg production.

Figs. 4 and 5 show the results of the contribution analysis for egg production in the current and target scenarios. The relative contribution of each input and the process emissions are shown for the evaluated impact categories. Among the inputs, feed is the greatest impact contributor followed by eggs, fuel (gas and diesel), electricity, pullet breeding, and equipment. The feed input is a significant contributor in all evaluated impact categories. In detail, feed is responsible of more than 50 % of the total impact in 12 impact categories: global warming, stratospheric ozone depletion, ionizing radiation, ozone formation (human), fine particulate matter formation, ozone formation (terrestrial), terrestrial acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, land use, and water consumption.

In the remaining six impact categories, the contribution from feed is less than 50 %, and the greatest contributors are the process emissions for terrestrial ecotoxicity, marine ecotoxicity, human non-carcinogenic toxicity, and human carcinogenic toxicity; the equipment manufacturing, maintenance and disposal for mineral resource scarcity; and the fuel consumption for fossil resource scarcity.

The composition and amount of feed are crucial factors in determining the life cycle of Iran's egg sector. The feed input is essential for both pullet breeding and egg production. To ensure sustainable management of egg production in Iran, feed should be prepared with minimal environmental impact. Growing maize and soyabean locally can reduce this impact. Additionally, changing the composition of consumed

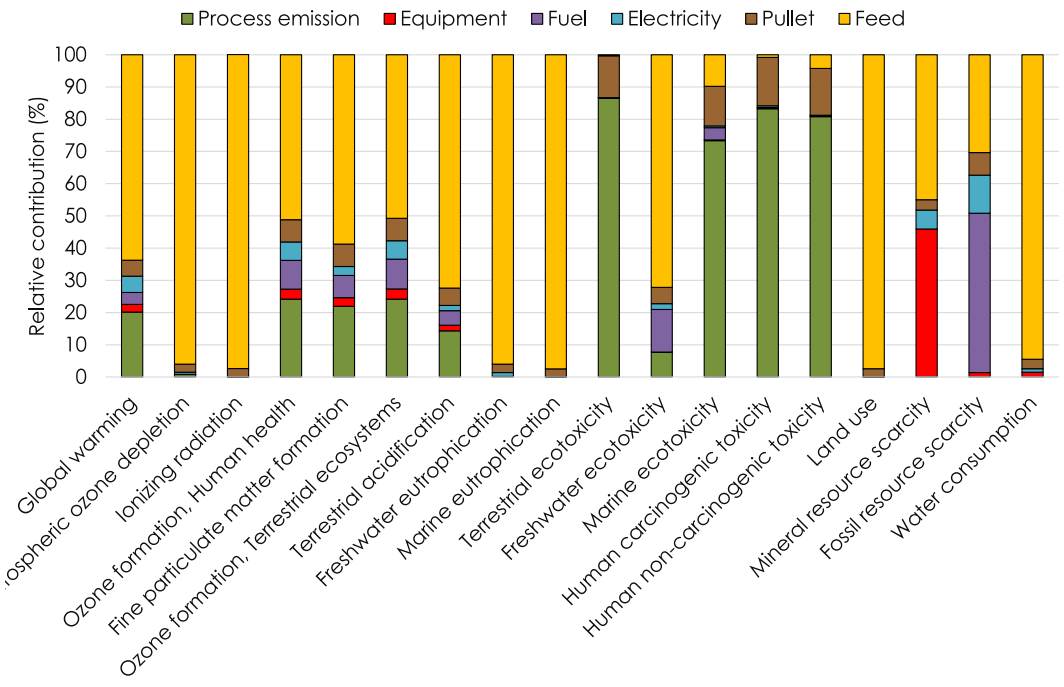


Fig. 4. Results of the contribution analysis for egg production in the current scenario, using the ReCiPe Midpoint method.

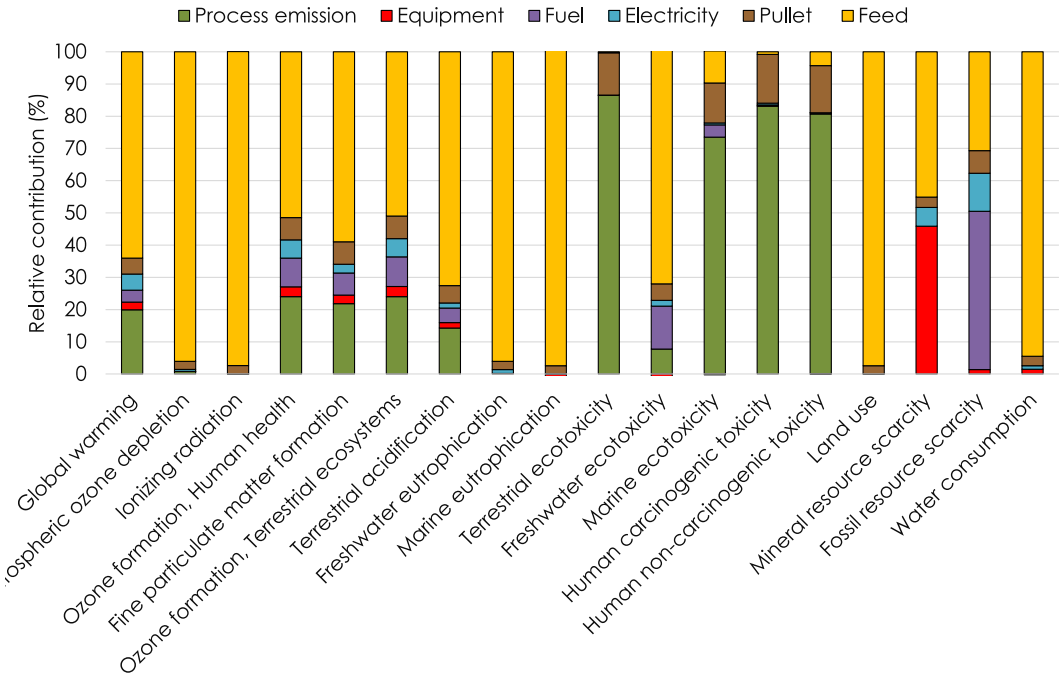


Fig. 5. Results of the contribution analysis for egg production in the target scenario, using the ReCiPe Midpoint method.

feed and using alternative ingredients with lower environmental impact can significantly control the overall environmental impact of the Iranian egg sector.

Pullet production accounts for less than 20 % of all environmental impacts. Electricity is consumed for equipment setup, including manure and egg collection, ventilation, lighting, and automatic feeding of food and water. Egg production farms consume more electricity than pullet farms due to the use of cages and automatic equipment, as well as a longer production period (546 days) than that of pullet farms (90 days). The overcrowding of laying hens in cages on egg production farms requires more efficient ventilation, automatic feeding, and egg and manure collection, as well as lighting, all of which increase electricity consumption. Similarly, egg production farms consume more fuel inputs, such as diesel fuel and natural gas, than pullet breeding farms. These fuels are utilized for heating equipment. Considering that fuel consumption significantly contributes to the environmental impact, new heating equipment (such as blower heaters, floor heating systems, solar heating systems, or jet heater heating systems) could be installed. This would reduce fuel consumption and improve the air in the halls, reducing the occurrence of respiratory diseases in laying hens.

Equipment only contributes significantly to mineral resource scarcity (42 % of the total impact), while for the other categories, its share of the

Table 8
Results of evaluating environmental indicators in the current and target scenarios for the production of 1 kg of eggs.

Impact category	Unit	Current	Target	Variation (%)
Global warming	kg CO_2 eq	4.398953	4.131713	6.07
Stratospheric ozone depletion	kg CFC_{11} eq	1.24E-05	1.17E-05	5.67
Ionizing radiation	kBq Co-60 eq	0.02588	0.024419	5.65
Ozone formation, human health	kg NO_x eq	0.005081	0.004771	6.09
Fine particulate matter formation	kg $PM_{2.5}$ eq	0.004087	0.003844	5.94
Ozone formation, terrestrial ecosystems	kg NO_x eq	0.005225	0.004907	6.09
Terrestrial acidification	kg SO_2 eq	0.021401	0.020153	5.83
Freshwater eutrophication	kg P eq	0.000331	0.000313	5.66
Marine eutrophication	kg N eq	0.003575	0.003374	5.63
Terrestrial ecotoxicity	kg 1,4-DCB	240.4882	224.5511	6.63
Freshwater ecotoxicity	kg 1,4-DCB	0.029067	0.027348	5.91
Marine ecotoxicity	kg 1,4-DCB	0.133849	0.125156	6.49
Human carcinogenic toxicity	kg 1,4-DCB	0.112482	0.10533	6.36
Human non-carcinogenic toxicity	kg 1,4-DCB	45.4557	42.57278	6.34
Land use	m2a crop eq	2.880443	2.717764	5.65
Mineral resource scarcity	kg Cu eq	0.00225	0.002116	5.95
Fossil resource scarcity	kg oil eq	0.724426	0.67684	6.57
Water consumption	m^3	0.036923	0.034829	5.67

impact is lower than 5 %. In accordance with veterinary laws in Iran, every egg production farm is required to have a manure warehouse to store waste and protect the environment. The manure storage must be equipped with net protection and be located at least 30 m away from the halls. Thus, the contribution of poultry farms to environmental impacts have increased due to manure.

Table 8 presents the absolute environmental results for 1 kg of eggs in current and target scenarios. The latter shows an impact reduction ranging from 5 to 7 % for all impact categories. Optimizing the management and consumption of feed can significantly reduce the environmental impact.

In both scenarios, the greatest impact contributor is feed production. The composition of materials and the feed consumed are the main contributors to global warming, followed by egg production (20 %), electricity (5 %), equipment (2 %), and natural gas (2 %). Turner et al. (2022) investigated egg production systems in Canada using DEA + LCA. They found that optimizing the consumption of feed and poultry inputs can reduce environmental effects by 17.27 % and maintenance costs by 3.22 %–3.55 % across all systems.

Fig. 6 shows the results of contribution analysis using the ReCiPe Endpoint method for the target scenario. In general, feed, with a share of 80 %, is the main contributor in the ecosystem damage category and has significant impacts on resources and human health (35 % and 33 %, respectively). For the latter damage categories, the main contributors are process emissions (58 % for human health) and fuel (50 % for resources). The role of equipment is always negligible (around 1 %); meanwhile, electricity plays a minor role in the human health and ecosystem damage categories but is responsible for 11 % of the impact in the resource damage category. Lastly, pullets show a contribution higher than 10 % for only human health (11 %).

The results of the present study emphasize the importance of assessing and managing the environmental impacts of inputs used in egg production. They also point to the need for targeted efforts to reduce the emission of environmental pollutants from the egg production process.

4. Conclusions

This study analyzed 14 pullet breeding farms and 40 egg production farms in Iran using the eco-efficiency method to optimize energy consumption and reduce environmental impact. The results show that energy consumption can be reduced by 6.5 % (from 1,606,307 to 1,501,117 MJ per 1000 laying hens). Proper management can lead to savings of 105,190 MJ per 1000 laying hens in the egg production chain. Optimizing and managing fuel and feed inputs can save energy while



Fig. 6. Results of the contribution analysis for egg production using the ReCiPe Endpoint method.

reducing the environmental impact. The study observed a 5–7 % decrease in all environmental impact categories, including a decrease in global warming from 4.40 to 4.13 kg CO_2 eq per kg of egg (−6.1 %). Feed input is the greatest contributor in all evaluated impact categories. Based on the results of the contribution analysis, feed is the greatest contributor of human health effects. Therefore, to reduce environmental effects, it is recommended to cultivate the main components of poultry feed (maize and soy) in Iran and use alternative ingredients in chicken feed. For future work, it is recommended to use modern systems and collect manure by conveyor belt because this reduces the environmental impact in the hall, improves chicken health, and requires less labor. Additionally, encouraging and supporting chicken farmers who use modern systems in egg production can influence attitudes and attract the attention of other farmers to adopt modern equipment for producing higher quality products with minimal environmental impact. Furthermore, it is important for relevant organizations to assist chicken farmers in equipping their farms, provide necessary facilities, and teach modern methods of egg production. This is a crucial step towards optimizing energy consumption and reducing environmental impact. Lastly, using labels to indicate the amount of greenhouse gas emissions in the production chain can effectively introduce cleaner products to both environmentalists and consumers. These research efforts provide stronger technical support to develop egg production, reduce environmental impact, and manage energy consumption more efficiently.

CRediT authorship contribution statement

Zahra Payandeh: Writing – original draft, Data curation, Conceptualization. **Tarahom Mesri-Gundoshmian:** Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Data curation, Conceptualization. **Ahmad Jahanbakhshi:** Writing – original draft, Validation, Supervision, Formal analysis, Data curation, Conceptualization. **Gholam Hosein Shahgholi:** Writing – original draft, Formal analysis, Conceptualization. **Lorenzo Rossi:** Writing – review & editing. **Jacopo Bacenetti:** Writing – review & editing.

Ethical approval

This study does not involve any human or animal testing.

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.

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Data availability

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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