Carbon footprint Assessment of Open Snail-Farm Systems in Central and Northern Greece

MARIANTHI HATZIIOANNOU*, KONSTANTINOS APOSTOLOU,
CHRISTOS DOMENIKIOTIS
Department of Ichthyology and Aquatic Environment,
School of Agricultural Sciences,
University of Thessaly
GREECE

*Corresponding Author

Abstract: - This study examines the environmental sustainability of open-field snail farming systems in Greece, focusing on their carbon footprint (CF) as a representative environmental impact metric. Eleven snail farms across Central and Northern Greece were analyzed using the Life Cycle Assessment (LCA) methodology, assessing inputs, outputs, and processes from farm construction to the point of sale. The results demonstrated significant variability in CF values, ranging from 0.048 to 7.65 kg CO_2 eq per kilogram of live snails. The primary contributors to CF were identified as the use of metal materials, electricity consumption for irrigation and drilling, and plowing. Farms with lower productivity exhibited disproportionately higher CF values, emphasizing the need for improved management practices. A comparative analysis with conventional livestock production highlighted snail farming as a more environmentally sustainable protein source, with significantly lower CF values, than cattle, pig, and poultry farming. Additionally, this study evaluates the environmental performance of heliciculture in Greece and proposes actionable strategies for enhancing sustainability in small-scale farming systems. Notably, transitioning from conventional electricity to renewable energy sources was shown to reduce the CF by up to 85%. These findings contribute to the broader discourse on sustainable protein production, offering valuable insights for both researchers and practitioners in agricultural sustainability.

Key-Words: - Environmental Sustainability, Life Cycle Assessment, Carbon footprint, Invertebrate Livestock, Heliciculture, Open farms.

Received: August 9, 2024. Revised: February 11, 2025. Accepted: March 19, 2025. Published: April 16, 2025.

1 Introduction

Designing ecological and environmentally sustainable food production systems requires a comprehensive analysis of the entire supply chain, from primary production and its inputs to the final product.

To achieve this, multiple supply chain scenarios must be developed to improve environmental performance without significantly altering the total quantity of the commodity produced—in this case, snail meat. This approach enables the experimental verification of the role played by various environmentally friendly products, whether as inputs or outputs, in promoting sustainable practices.

Heliciculture, the farming of snails, has been practiced since the 1st century B.C. and is now commercially undertaken in regions such as France, Italy, Greece, Spain, China, Australia, and parts of North and South America. These regions utilize both extensive and intensive farming methods, [1], [2], [3]. Terrestrial snails are not only a high-value food product but also a source of specialized items such as caviar, mucus, and bioactive compounds with significant commercial value. In the long term, consumable invertebrates, including snails, represent a potential sustainable protein source for a global population projected to reach nine billion by 2050, [4].

Several laboratory experiments have been conducted to optimize snail production. However, relatively few studies have been carried out on actual snail farms. [5] investigated the effects of stocking density, finding that lower densities led to increased consumption and growth rates, with a higher proportion of gastropods reaching adulthood. In external fattening parks, [6] determined that biotic load of 50 g/m² for snails between three weeks and one month (*Helix aspersa*) was optimal for mixed rearing, yielding approximately 3 kg/m² of marketable snails over five months, with 89% reaching marketable size. [7] examined adult *Helix aspersa* land snails at three stocking densities in outdoor systems to enhance understanding of spatial allocation and behavioral patterns. Similarly, [3] evaluated the carbon footprint (CF) of a semi-intensive snail farm in a Mediterranean setting.

The ecological footprint of conventional livestock farming necessitates fundamental shifts in both meat consumption patterns and alternative production systems. Farmed snails offer a sustainable alternative to traditional livestock [3]. Studies comparing the environmental impacts of common meat sources, such as cattle, pigs, and poultry, indicate that snails significantly reduce impacts across almost all categories, [8]. In the Mediterranean region, wild snail populations have declined due to overharvesting for food, emphasizing the importance of farming, [9]. Despite this, no comprehensive surveys have been conducted on production practices for breeding gastropods.

In recent years, small farming systems have attracted significant research attention due to their high energy and water consumption, as well as their substantial waste generation. These systems face increasing commercial and societal pressure to reduce their environmental footprint and adopt more sustainable practices. Regional authorities emphasize balancing economic growth with environmental preservation as a fundamental goal, [10].

Heliciculture, or snail farming, exemplifies this challenge. Across European regions, small farming systems display notable differences in agricultural structure and resource utilization, leading to significant variability in pollution load emissions. Modern technology adoption determines whether such systems employ intensive or extensive production methods, while organic farming prioritizes environmental conservation and positively impacts surrounding ecosystems, [11]. However, the complexity and resource demands of small-scale snail farming require a comprehensive evaluation of its environmental interactions. This necessitates a detailed analytical approach to assess resource usage, emissions, and other key environmental factors while identifying opportunities for system improvements, [12].

LCA provides a comprehensive framework for quantifying, evaluating, comparing, and enhancing the environmental impacts of products and services, [13]. By analyzing every stage of a product's lifecycle—from raw material extraction and usage to emissions and disposal—LCA offers valuable insights into environmental burdens while incorporating societal and economic dimensions. This "triple helix" approach of environmental conservation, societal needs, and economic growth underpins life cycle sustainability assessments, [14]. For farmers and producers, LCA also serves as a tool for addressing consumer and environmental concerns related to the ecological footprint of agricultural products.

Numerous studies have applied LCA and sustainability assessments to evaluate the environmental impacts of small-scale heliciculture systems, [3], [15], [16], [17], [18]. These studies primarily assess factors such as global warming potential, eutrophication, energy consumption, and CO_2 emissions. However, despite these efforts, a notable knowledge gap remains regarding the environmental contributions of heliciculture-based farming systems within the broader Greek region.

This manuscript addresses this gap by presenting the general characteristics of the study area, the data collection methodologies, and the specific attributes of the farms analyzed. This categorization aids in identifying the inclusion or exclusion of various raw materials for the subsequent LCA. The models and materials used for the LCA are detailed in the methodology section, while the results and comparisons are presented and discussed in later sections, culminating in the conclusions drawn from the analysis.

This paper is novel in several aspects and is of critical significance for publication as it addresses a pressing knowledge gap by providing the first quantitative assessment of the environmental performance of Greek heliciculture farming systems. By applying the LCA methodology, this study systematically evaluates the carbon footprint of open snail farms across 11 sites in Central and Northern Greece. The findings offer a detailed analysis of key environmental contributors, such as material use, energy consumption, and farming practices, providing practical insights for reducing environmental impacts. Additionally, this study is among the few that assess the whole life cycle of snail farming including product transportation to market. Furthermore, it compares the environmental load of snail farming with that of traditional livestock and insect protein production, highlighting heliciculture as a sustainable protein source. With its focus on regional challenges and solutions, this research contributes valuable data to the pursuit of sustainable farming practices while supporting global efforts aimed at reducing the environmental footprint of food production.

2 Materials and Methods

2.1 Goal and Scope

The primary goal of this study was to evaluate the environmental impact of snail breeding in an open field, using LCA.

Specifically, a thorough analysis was conducted to evaluate the individual contributions of all installations and feeling products to the CO_2 emissions.

Additionally, the study aimed to suggest improvements such as transitioning from conventional electricity to renewable sources, to reduce the CF. Renewable energy was selected as an ideal solution due to its potential for energy-saving technology, [19]. The analysis focuses on snail farming systems in Greece, presenting an LCA on 11 snail farms distributed across the country as a case study in heliciculture.

2.2 Area of Experiment

This study was conducted in 11 open snail farms located in four regions of Central and Northern Greece: Central Macedonia, Western Macedonia, Eastern Macedonia, and Thrace and Thessaly (Figure 1). The species cultivated for human consumption were *Cornu aspersum maximum* and *Cornu aspersum aspersum*. According to the Hellenic National Meteorological Service, Greece has a Mediterranean climate, characterized by mild, rainy winters and comparatively warm, dry summers with extended periods of sunshine throughout the year.

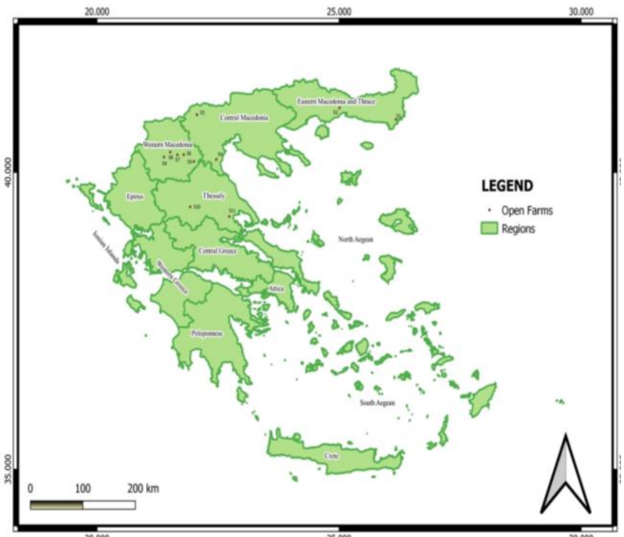

Fig. 1: Geographical distribution of the 11 open-field snail farms studied in Central and Northern Greece

However, due to the variations in topography and moisture sources from the central Mediterranean Sea, different regions experience distinct climate subtypes. Broadly, climate can be divided into two seasons: cold and rainy (October to March) and warm and dry (April to September). The coldest months are January and February with average minimum temperatures ranging from 5°C - 10°C along the coasts and 0°C - 5°C on the mainland. Sub-zero temperatures are mainly observed in the northern regions. The rainfall is generally short-lived. The warmest months, July and August, have average maximum temperatures between 29°C and 35°C.

2.3 Snail Farming System

In an open farm, all breeding stages (reproduction, egg incubation, and hatching, brood fattening) occur within a fenced area where plants are cultivated under environmental conditions, [15]. The rearing period required for snails to reach commercial size ranges from 9 to 18 months.

The total area of the open snail farms in this study varies between 2000 and 15000 m^2 (Table 1). The farms are enclosed externally with stainless steel sheet fencing, reaching a total height of 2 meters. The perimeter is reinforced with an iron plate and wire mesh.

Each farm is divided into smaller sections using a sieve made of non-toxic polyethylene. Inside these sections, broadleaf plants (cabbage, lettuce) are cultivated, while wooden shelters are placed. A plastic feeder is positioned underneath to prevent direct contact with water. Irrigation system maintains relative humidity at predefined levels (75 – 80%). It consists of watering hoses (polyethylene) and injectors, ensuring adequate coverage for the entire area. To facilitate optimal farm operation, an irrigation was drilled.

All preparations in the breeding area began 2 months before the snails were placed on the farm. The process includes plowing the substrate and cultivating plants. In each farm, plants serve as complementary diets for the farmed snails while also contributing to retaining moisture, providing shelter, and offer shading. Before plowing, soil analysis is essential. Also, disinfecting the field with chlorpyrifos is important. For plant cultivation, 350 gr of seeds from each plant were sown per farm, followed by manual fertilization. The warehouse, constructed from steel panels and polyurethane serves as a temporary storage for snails after harvest, as well as for tools and materials essential to the production process. Furthermore, agricultural machinery and tools required for farm operations are rented as needed, with their power not exceeding 5 hp.

Table 1. Overview of data collected from the 11 open snail farms based on *in-situ* visits and farmer questionnaire

Code	Farming area (m^2)	Total Production (Kg/year)	Snail species
S1	5000	1000	*Cornu aspersum maximum*
S2	3000	1500	*Cornu aspersum maximum*
S3	3000	3000	*Cornu aspersum maximum*
S4	3700	370	*Cornu aspersum maximum / Cornu aspersum*
S5	10000	1000	*Cornu aspersum maximum*
S6	6000	1000	*Cornu aspersum maximum*
S7	5000	2500	*Cornu aspersum maximum*
S8	5000	2500	*Cornu aspersum maximum*
S9	15000	2000	*Cornu aspersum maximum*
S10	2000	1600	*Cornu aspersum maximum*
S11	15000	8250	*Cornu aspersum*
Average	6609	2247	

2.4 Functional Unit

As the functional unit for assessing snail breeding, was set 1 kg of fresh live snails for consumption.

2.5 System Boundaries

A life cycle approach was adopted using a "cradle to retail", meaning that the environmental impact was assessed up to the point of sale. This included transportation from the snail farm to the market or the food processing industry.

Additionally, the study considered soil preparation, cultivation, fertilization, disinfection, plastic or wooden auxiliaries, and electricity production. It also includes snail feeding, rearing, hatchery, harvesting, packaging (including required materials), and distribution of the final product. However, the system boundaries excluded the production of construction materials, the feed production process at mills, and the disposal of snail wastes.

The environmental inputs and outputs of the product are compiled and quantified throughout its life cycle. Environmental inputs include structural components, rearing processes, and transportation.

Snail feces, composed of nitrogen-rich organic matter are not discarded but remain on the ground as fertilizer. As a result, they are considered both input and output so they are excluded from the carbon footprint calculations.

Similarly, snail shells and plant residues are retained in the soil of the farm in order to enrich it with calcium and organic matter, respectively, [3].

In this research, CO2 emissions from land-use change were not calculated due to a lack of methodology, despite their recognized impact on the final carbon footprint, [20], [21], [22], [23]. Furthermore, potential long-term carbon storage in the snail shells which could capture CO2 andpossibly reduce the carbon by 18% [3], was not taken into account. The system boundaries along with the associated inputs and processes, are illustrated in Figure 2.

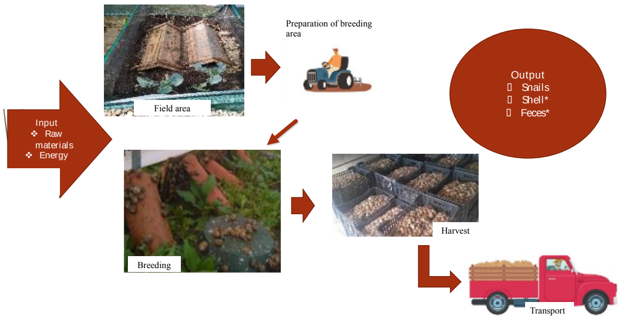

Fig. 2: Flowchart showing the stages from the construction of snail farms to the transportation of the final product, before this is placed on the market

2.6 Life-Cycle Inventory

As heliciculture expands rapidly in southern European countries, the environmental impact of snail farming has become a scientific concern. More specifically this research focuses on the life cycle assessment mainly represented by the carbon footprint (CF) of such farming activities. It is important to note that snail meat represents an environmentally friendly alternative to conventional livestock.

However, very little is known about the environmental impact of heliciculture. The most notable study was conducted by [3], which evaluates greenhouse gas emissions affiliated with different rearing phases (breeding, fattening, clearance, and packaging), as a case study for Southern Italy, taking into account the shell's potential for CO_2 sequestration. Following the Life Cycle Assessment (LCA) methodology, this research aimed to analyze the environmental aspects and potential impacts throughout a product's life cycle - from the purchase of raw materials to the end-of-life processes such as recycling, and disposal. Regarding the 11 snail farms mentioned in section 2.2, our study focuses on assessing inputs, outputs, and potential environmental impacts of the product system throughout its life cycle.

The data collection corresponds to the second phase of the LCA methodology (viz. Life cycle inventory analysis (LCI)). Each stage of the snail production was considered to contribute to the overall carbon footprint. Therefore, factors such as raw material, farm construction and operation, transportation, energy consumption, and production processes – up to the point before the product reached the market – were all included. To accurately determine the environmental impacts of the product systems (open farms), excluding any of these stages would have altered the final carbon footprint. Consequently, a comprehensive report of snail farm systems and their characteristics was compiled through a designated questionnaire. First, contact was established with the owners of the 11 heliciculture farms in the study area. Site visits were conducted to gather all necessary data and information required to quantify the environmental impact, particularly for calculating the carbon footprint (CF), associated with the construction and operation of these farms. The collected data was structured in order to facilitate the input-output flow of the LCA (Figure 2) and was obtained through *in situ* visits [15] during the spring and summer of 2017. The research tools used during the field survey, included a structured questionnaire, with open, closed, divisional, and multiple-choice questions, as well as unstructured interviews. The acquired data was categorized into three main areas, (Table 2): (a) structure–field area, (b) rearing, and (c) transport. Each category further divided into subcategories to cover all aspects of the process (a detailed description of certain inputs is provided by [15].

Table 1 and Table 2 present the data collected from the above processes for each farm. In general, the first category (structure-field area) shows several common structures (iron plate, wire mesh, and watering hoses-injections). However, some farmers used fabric for low temperatures and shelters. The second category exhibits greater variability across all subcategories, while in the third category, all farmers use the same transportation. This suggests that structural and transport inputs are relatively consistent across all open farms. The collected data from the open snail farming system, as described above, was organized into tabular format and standardized to units per 1000m^2 per year.

2.7 System Inputs

The majority of snail farmers in this study used a compound diet for snails (400 – 2500 kg), supplemented with existing plants. Only one open farm relied solely on plant-based feeding. This diet consisted of wheat-fed flour for animal feed and calcium carbonate (70 – 30%). Total snail production per farm ranged from 100 Kg/year to 8250 Kg/year (Table 1). The average annual manure amount in farms was 20 Kg (Table 2). Additionally, zeolite was used as a fertilizer in 3 farms (45.83 Kg). The transport of the final product from the farm to market or processing industry was also assessed. Snails were transported using small trucks.

Table 2 presents the total materials used across all surveyed snail farms. The categorization includes raw materials, electricity (energy), industrial structures, and various auxiliary elements that support each stage of production, along with the side buildings. To meet the operational needs of drilling, lighting, and other activities, the farm was connected to the electricity network. Electricity consumption was estimated based on farm records. For each material input listed in Table 2, durability was assessed and divided by its approximate lifespan to calculate annual values. Indicative values were obtained from the OpenLCA globally recognized database system and were slightly adjusted to better represent the materials commonly used in the surveyed Greek farms.

Table 2. Overview of materials and inputs used in the LCA for CO2eq calculation, including descriptive statistics and the number of farms (N) in which each material was used

LCA	N	Quantity				Unit
		Min	Max	Average	St. Dev.	
A. Structure - Field area						
Steel hot - dip galvanized coil	11	10,05	2057,70	794,25	921,89	Kg
Wooden pallet	6	5,33	116	49,2	45,34	Kg
Polyethylene high density granulate	11	2,68	22,17	7,83	5,18	Kg
B. Rearing						
B1. Preparation of breeding area						
Chlorpyrifos	7	2,5	20,00	8,08	7,32	Kg
Ploughing with 1 soc plough	9	3	10	4,56	2,19	Day
Manure	3	10	40	20	17,32	Kg
Zeolite	2	8,33	83,33	45,83	53,03	Kg
Electricity mix	7	1260	8400,00	3216,43	2363,03	MJ
Drinking water	11	240	2800	910,36	670,58	Kg
B2. Breeding						
Calcium carbonate	11	1,07	178,38	89,83	72,72	Kg
Carrot seed, conventional at farm gate	9	0,06	3,50	0,67	1,08	Kg
Wheat feed flour, animal feed	10	100	1000	320	264,55	Kg
Sunflower, Seed	1	1,17	1,17			Kg
B3. Harvest						
Polypropylene granulate (PP)	11	1,09	4,41	2,26	1,04	Kg
C. Transport						
Transport in t*km	11	46,1	378	165,22	100,98	t*km
Gasoline	11	3,23	26,46	11,57	7,07	L

2.8 Statistical Analysis

For the statistical analysis, descriptive statistics of the input quantities were calculated and are presented in Table 2. The mean, standard deviation, minimum and maximum values, were determined for each input parameter. To assess whether there were statistically significant differences in the mean carbon footprint between the 2 farm categories: large (over 5000 m^2) and medium (under 5000 m^2), the Mann–Whitney test was performed at a significance level of a = 0.05.

3 Results

3.1 Carbon Footprint

As indicated in Figure 3 for the total sample of 11 surveyed open snail farms, the average CF was calculated at 2.61 Kg CO2eq. However, there was considerable variation among the farms, with values ranging from 0.05 to 7.66 Kg CO2eq. Farm S5 exhibited the highest CF (7.66 Kg CO2eq), while two other farms (S7 – 5.12; S6 – 4.82) also had significantly high values. In contrast, three farms recorded nearly negligible footprints (S1 – 0.05; S8-0.152; S4 – 0.237). Additionally, two farms had slightly higher than average values (S10 – 2.81; S11- 3.37). Finally, the remaining three had carbon footprints below 2 Kg CO2eq (S9 -1.14; S2 – 1.50; S3 – 1.86). Notably, the highest Carbon Footprint values are observed in farms located in Western Macedonia.

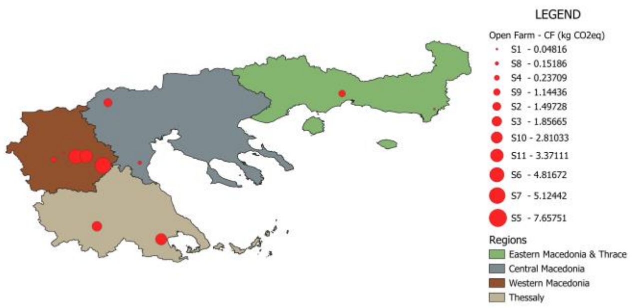

Fig. 3: Geographic distribution of the open farms and their carbon footprint values. Farm-specific emissions are represented by proportional red circles

Three main factors primarily contribute to the carbon footprint of open snail farms (Figure 4):

1. Use of metal materials (sheet metal, galvanized coil, iron plates & fencing mesh), which accounted for the largest contribution in 5 farms (70 – 92%),
2. Electricity consumption (in 3 farms: 59 – 85%) primarily used for drilling and irrigation,
3. Ploughing (tractor or milling machine) with higher percentages recorded in 3 farms (67 – 89%).

Metal materials are mainly used externally as fencing (stainless steel sheets and wire mesh) surrounding the entire area. Additionally, steel sheets are used for rodent protection and to support the plastic sieves that divide the sections where the snails are reared. Steel is also used in the construction of warehouses.

Electricity consumption is mainly required for drilling operations and, in many cases, for the automatic operation of the cooling systems. In a few farms lighting and ventilation are also used in warehouses where the snails are stored before sale.

The carbon footprint associated with plowing, which includes the use of agricultural machinery, is attributed to the farmer. As shown in Table 2, some farmers plow their farms three times a year, while others plow up to ten times annually, significantly increasing their carbon footprint. This practice has not been proven to enhance production or improve snail welfare and, given its high environmental impact, is considered inefficient.

Slightly smaller contributions to the CF (Figure 4) come from fuel consumption for agricultural machinery and the transportation of raw materials or final products. Finally, the least significant factor in the carbon footprint is calcium, which is incorporated into snail feed.

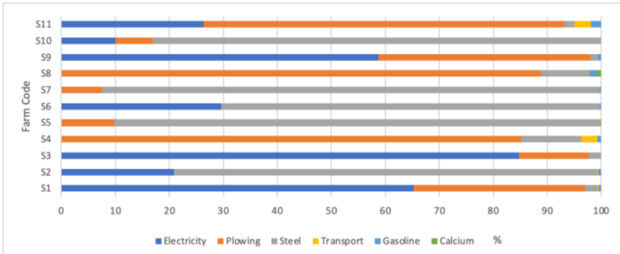

Fig. 4: Percentage contribution of key factors to the Carbon Footprint of each open snail farm

The lowest CF recorded in this study was observed in the S1 farm, amounting to 0.04816 Kg CO2eq. The largest contributor to its CF was electricity consumption, accounting for 65.25% (Figure 5). The second most significant factor was ploughing which contributed 31.73% of the total carbon footprint. In contrast, metal usage in this farm had a much smaller share (2.32%) followed by fuel consumption (0.5%). Transportation of the final product had the least impact (0.2%).

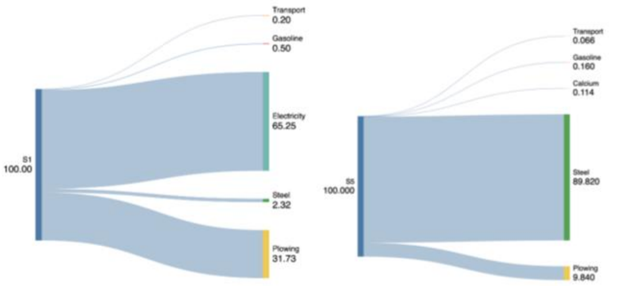

Fig. 5: Sankey diagram of Carbon footprint distribution in S1 (lowest CF) and S5 farm (highest CF) farms. The percentages indicate the impact of key factors on the CF

In the farm with the highest amount of CF (S5), the largest contributor was metal materials, accounting for (89.82%). Plowing contributed 9.84%, while transportation of products, fuel consumption, and calcium carbonate used in the snail diet had minimal contributions, each accounting for less than 0.2%.

Figure 6 illustrates that when snail farms reach their maximum productivity (1000Kg/year/1000m^2), they achieve the lowest Carbon footprint. Significantly, the 2 farms with the highest carbon footprint (S5 and S7) produced only 100 kg/1000 m^2. If these farms operated at full productivity, their carbon footprint would drop below 0.5 %.

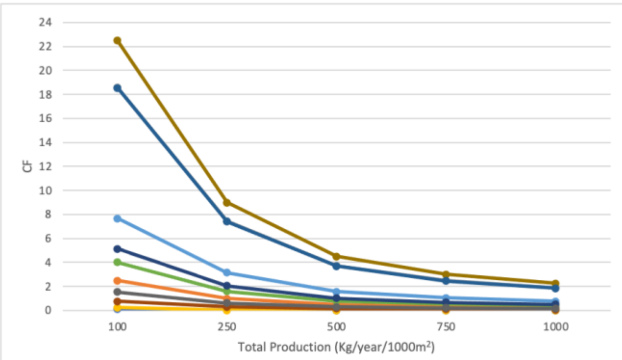

Fig. 6: The carbon footprint of each snail farm under 5 different production scenarios (10%, 25%, 50%, 75%, and 100% of maximum productivity)

3.2 Mitigating Carbon Footprint by Integrating Renewable Energy

The alternative solution selected in this research to minimize the environmental impact of snail breeding was the transition from conventional electricity to renewable energy sources. As a case study, we examined 4 snail farms (S3, S6, S9, S11) that exhibited the highest electricity consumption in combination with high CF.

Results indicate a reduction of up to 85% (Table 3), with the lowest value reaching 0.22606 kg CO2eq in the S9 snail farm.

Table 3. Reduction in Carbon Footprint (CF) after transitioning to renewable energy sources for 4 open snail farms with the highest energy consumption

Code	CF (Kg CO2eq) (Conventional Electricity)	CF (Kg CO2eq) (Renewable sources)	Footprint Reduction (%)
S3	1.85665	0.47419	74.46
S6	4.81672	0.75831	84.25
S9	1.14436	0.22606	80.25
S11	3.37111	0.87809	73.95

3.3 Statistical Analysis

The results of this study indicate no statistically significant difference in the CF between the two categories of farming systems (medium-large). The significance value (p) from the Mann–Whitney test was 0.164, which is greater than 0.05; meaning that the difference between them is not statistically significant.

4 Discussion

In this study, following the LCA methodology and focusing on 11 heliciculture farms, we evaluated the inputs, outputs, and potential environmental impacts of the product system throughout its life cycle. The key contributors to the carbon footprint of producing 1 kg of snails were highlighted. Electricity consumption, plowing, metal materials, and transportation are the main hotspots in the snail breeding process. Metal materials are primarily used in the construction phase of the heliciculture units, while electricity and plowing are associated with the breeding phase. Finally, transportation of products to and from the farm has a lower overall contribution, as also noted by [3], who found that transporting snail feed to the farm accounted for approximately 3% of total CF. In contrast, studies on various farmed animals have shown that product transportation can significantly increase the carbon footprint, reaching up to 20%, [23].

Data on the CF of other animal production systems (cattle, pigs, poultry) are also presented and compared to the results of this study. Research on life cycle assessments of beef production indicates that it has the highest environmental impact among livestock, followed by pork and chicken, [24]. The carbon footprint of beef ranges from 22.2 kg CO2eq to 24.62 kg CO2eq [25], [26], nearly three times higher than the highest recorded value for an open snail farm in Greece. The CF levels from the surveyed snail farms were categorized into 3 groups.

Three farms exhibited a high CF, with an average of 5.87 Kg CO2eq. This value is comparable to the CF observed in sheep milk production (3.58 kg of CO2eq, [27], 4.09 kg of CO2eq, [28]) and pork meat (3.39 kg CO2eq, [29]).

Five snail farms exhibited an average CF of 2.14 kg CO2eq. This value is comparable to chicken production, which ranges from 2.03 to 2.22 tons CO_2-eq/ton of live weight, [30]. Additionally, insect production has been reported to have similar CF values. For instance, 1 Kg of crickets resulted in 2.29 kg CO2eq [31] while 1 kg of mealworms had a CF of 2.7 kg CO2eq, [32]. Furthermore, migratory beekeeping systems have been reported to have a similar carbon footprint (1.40-2.20 kg CO2e/kg honey), [33].

Meanwhile, 3 open farms exhibited a low CF (0.146 kg CO2eq). These results align with those of [3] and [8], who also found that open snail farms in Italy had a lower CF compared to other types of livestock farming. Notably, the only comparable production system is mussel cultivation, as recent studies indicate that mussel production has a low CF (0.07 to 0.95 kg CO2eq), [34], [35].

This study suggests that if all open snail farms reach their maximum productivity (1000 Kg/year/1000m^2) and transition from semi-intensive to extensive farming systems, they will achieve the lowest possible CF. These findings are consistent with the literature, as [27] and [28] report similar trends in dairy sheep farms.

The transition from conventional electricity to renewable sources has been shown to reduce carbon and greenhouse gas (GHG) emissions, enhance the adoption of environmentally friendly technologies [36], and promote environmental sustainability, [37]. In our study this change, led to a reduction in the CF (up to 85%), similar to findings in other livestock farms where a decrease in potential greenhouse gas (GHG) emissions [38] was observed. This shift improves the environmental profile of open snail farms. Additionally, since electricity consumption is the 2nd largest expense for snail farmers, adopting renewable energy presents a viable strategy for reducing production costs.

5 Conclusion

This study is among the few LCA analyses conducted on snail farming systems and the first one in Greece. Additionally, it is the only research to date that evaluates the CF of 11 open snail farms.

The primary objective was to identify the production inputs with the highest contribution to the carbon footprint of producing 1 kg of snails in open farms in Greece and to establish the environmental profile of these farms.

The use of metal materials, electricity consumption, and plowing had the most significant impact on the environmental footprint of open snail farms.

The average CF value observed was slightly higher than that reported in a similar study conducted in Italy.

Overall, this research highlights the potential reduction in environmental impact if snail farms operate at full productivity. It reinforces the idea that improved management of the breeding process by farmers can maximize productivity while simultaneously reducing the carbon footprint.

The LCA results contribute to expanding research in heliciculture, as comparing these results with data on conventional livestock (beef, pork, chicken) and insect protein production confirms that snail farming is among the most environmentally friendly protein sources, given its remarkably low CF.

A natural progression of this study would be to examine CF of mixed systems and net-covered greenhouse snail farms (intensive farming systems), which are widely practiced in many countries but remain largely unstudied. These systems require more energy and materials, necessitating an assessment of their footprint and proposing alternative solutions to minimize environmental impact while ensuring that farmers do not lead to financial losses.

Acknowledgement:
We would like to thank Dr. K.N. Kokkinos for his constructive suggestions. We are also grateful to the snail farm owners for their collaboration.

Declaration of Generative AI and AI-assisted Technologies in the Writing Process

The authors wrote, reviewed and edited the content as needed and they have not utilised artificial intelligence (AI) tools. The authors take full responsibility for the content of the publication.

References:

[1] Bonnet, J.-C.; Aupinel, P.; Vrillon, J.-L. *L'escargot Helix aspersa: Biologie-élevage*; Quae, 2019; ISBN 978-2-7592-3007-5.

[2] Ligaszewski, M.; Pol, P.; Radkowska, I.; Surówka, K.; Łysak, A. Results of Research on the Active Species Protection of the Roman Snail (Helix Pomatia, Linnaeus, 1758) Using Farmed Snails in the Second Year of Life. First Season of the Study. *Ann. Anim. Sci.* 2014, *14*, 377–389, doi: 10.2478/aoas-2013-0068.

[3] Forte, A.; Zucaro, A.; De Vico, G.; Fierro, A. Carbon Footprint of Heliciculture: A Case Study from an Italian Experimental Farm. *Agric. Syst.* 2016, *142*, 99–111, doi: 10.1016/j.agsy.2015.11.010.

[4] Gerber, P.J.; Steinfeld, H.; Henderson, B.; Mottet, A.; Opio, C.; Dijkman, J.; Falcucci, A.; Tempio, G. *Tackling Climate Change through Livestock: A Global Assessment of Emissions and Mitigation Opportunities.*; 2013; ISBN: 92-5-107920-X.

[5] Dupont-Nivet, M.; Coste, V.; Coinon, P.; Bonnet, J.-C.; Blanc, J.-M. Rearing Density Effect on the Production Performance of the Edible Snail Helix Aspersa Müller in Indoor Rearing. *Ann. Zootech.* 2000, *49*, 447–456, doi: 10.1051/animres:2000135.

[6] Daguzan, J. Recherché Ecophysiologiques Sur l'escargot Petit-Gris (Helix Aspersa Müller) En Vue de Son Élevage.; 1992; Vol. 13, pp. 113–124.

[7] González, O.; Pérez Camargo, G.; Membiela, M.; Frezza, D.; Bartoloni, N.; Vieites, C. Discrete Observations of the Spatial Distributions of the Helix Aspersa Snail in an Outdoor System. *Cienc. E Investig. Agrar.* 2009, *36*, doi: 10.4067/S0718-16202009000100012.

[8] Zucaro, A.; Forte, A.; De Vico, G.; Fierro, A. Environmental Loading of Italian Semi-Intensive Snail Farming System Evaluated by Means of Life Cycle Assessment. *J. Clean. Prod.* 2016, *125*, 56–67, doi: 10.1016/j.jclepro.2016.03.045.

[9] Lazaridou-Dimitriadou, M.; Alpoyanni, E.; Baka, M.; Brouziotis, TH.; Kifonidis, N.; Mihaloudi, E.; Sioula, D.; Vellis, G. Growth, Mortality and Fecundity In Successive Generations of Heix Asersa Müller Cultured Indoors and Crowding Effects on Fast-, Medium- and Slow-Growing Snails of the Same Clutch. *J. Molluscan Stud.* 1998, *64*, 67–74, doi:10.1093/mollus/64.1.67.

[10] Florindo, T.J.; Florindo, G.I.B. de. M.; Talamini, E.; Costa, J.S. da.; Léis, C.M. de; Tang, W.Z.; Schultz, G.; Kulay, L.; Pinto, A.T.; Ruviaro, C.F. Application of the Multiple Criteria Decision-Making (MCDM) Approach in the Identification of Carbon Footprint Reduction Actions in the Brazilian Beef Production Chain. *J. Clean. Prod.* 2018, *196*, 1379–1389, doi: 10.1016/j.jclepro.2018.06.116.

[11] De Luca Peña, L.V.; Taelman, S.E.; Préat, N.; Boone, L.; Van der Biest, K.; Custódio, M.; Hernandez Lucas, S.; Everaert, G.; Dewulf, J. Towards a Comprehensive Sustainability Methodology to Assess Anthropogenic Impacts on Ecosystems: Review of the Integration of Life Cycle Assessment, Environmental Risk Assessment and Ecosystem Services Assessment. *Sci. Total Environ.* 2022, *808*, 152125, doi: 10.1016/j.scitotenv.2021.152125.

[12] Kovacic, I.; Waltenbereger, L.; Gourlis, G. Tool for Life Cycle Analysis of Facade-Systems for Industrial Buildings. *J. Clean. Prod.* 2016, *130*, 260–272, doi: 10.1016/j.jclepro.2015.10.063.

[13] Alejandre, E.M.; van Bodegom, P.M.; Guinée, J.B. Towards an Optimal Coverage of Ecosystem Services in LCA. *J. Clean. Prod.* 2019, *231*, 714–722, doi: 10.1016/j.jclepro.2019.05.284.

[14] Morone, P.; Caferra, R.; D'Adamo, I.; Falcone, P.M.; Imbert, E.; Morone, A. Consumer Willingness to Pay for Bio-Based Products: Do Certifications Matter? *Int. J. Prod. Econ.* 2021, *240*, 108248, doi: 10.1016/j.ijpe.2021.108248.

[15] Apostolou, K.; Staikou, A.; Sotiraki, S.; Hatziioannou, M. An Assessment of Snail-Farm Systems Based on Land Use and Farm Components. *Animals* 2021, *11*, 272, doi: 10.3390/ani11020272.

[16] Jeanneret, P.; Baumgartner, D.U.; Freiermuth Knuchel, R.; Koch, B.; Gaillard, G. An Expert System for Integrating Biodiversity into Agricultural Life-Cycle Assessment. *Ecol. Indic.* 2014, *46*, 224–231, doi: 10.1016/j.ecolind.2014.06.030.

[17] Grossi, G.; Chiriacò, M.V.; Castaldi, S.; Valentini, R. Carbon Footprint of Snail Meat: A Case Study from an Italian Organic Outdoor Rearing.; Ravenna, Italy, 2016; Vol. Proceedings of the 10th Convegno dell'Associazione Rete Italiana LCA.

[18] Prechsl, U.E.; Wittwer, R.; van der Heijden, M.G.A.; Lüscher, G.; Jeanneret, P.; Nemecek, T. Assessing the Environmental Impacts of Cropping Systems and Cover Crops: Life Cycle Assessment of FAST, a Long-Term Arable Farming Field Experiment. *Agric. Syst.* 2017, *157*, 39–50, doi: 10.1016/j.agsy.2017.06.011.

[19] Orlov A. V., Transition to a Green Economy through the Development of Renewable Energy in the European Union. *WSEAS Transactions on Environment and Development,* 2024, *20*, 1072–1084, https://doi.org/10.37394/232015.2024.20.98.

[20] Dudley, Q.M.; Liska, A.J.; Watson, A.K.; Erickson, G.E. Uncertainties in Life Cycle Greenhouse Gas Emissions from U.S. Beef Cattle. *J. Clean. Prod.* 2014, *75*, 31–39, doi: 10.1016/j.jclepro.2014.03.087.

[21] MacLeod, M. *Greenhouse Gas Emissions from Pig and Chicken Supply Chains – A Global Life Cycle Assessment*; Food and Agriculture Organization of the United Nations (FAO).; Rome, 2013; ISBN: 978-92-5-107944-7.

[22] Röös, E.; Sundberg, C.; Tidåker, P.; Strid, I.; Hansson, P.-A. Can Carbon Footprint Serve as an Indicator of the Environmental Impact of Meat Production? *Ecol. Indic.* 2013, *24*, 573–581, https://doi.org/10.1016/j.ecolind.2012.08.004.

[23] Nijdam, D.; Rood, T.; Westhoek, H. The Price of Protein: Review of Land Use and Carbon Footprints from Life Cycle Assessments of Animal Food Products and Their Substitutes. *Food Policy* 2012, *37*, 760–770, doi: doi.org/10.1016/j.foodpol.2012.08.002.

[24] Zervas, G.; Tsiplakou, E. Life Cycle Assessment of Animal Origin Products. *Adv. Anim. Biosci.* 2016, *7*, 191–195, doi: 10.1017/S204047001600011X.

[25] Jacobsen, R.; Vandermeulen, V.; Vanhuylenbroeck, G.; Gellynck, X. A Life Cycle Assessment Application: The Carbon Footprint of Beef in Flanders (Belgium). In *Assessment of Carbon Footprint in Different Industrial Sectors, Volume 2*; Muthu, S.S., Ed.; Springer: Singapore, 2014; pp. 31–52 ISBN: 978-981-4585-75-0.

[26] Buratti, C.; Fantozzi, F.; Barbanera, M.; Lascaro, E.; Chiorri, M.; Cecchini, L. Carbon Footprint of Conventional and Organic Beef Production Systems: An Italian Case Study. *Sci. Total Environ.* 2017, *576*, 129–137, https://doi.org/10.1016/j.scitotenv.2016.10.075.

[27] Ravani, M.; Liantas, G.; Alvanou, M.V.; Tampaki, E.; Chatzigeorgiou, I.; Giantsis, I.A.; Ntinas, G.K. Life Cycle Analysis of Semi-Intensive and Intensive Sheep Milk Production. *Int. J. Life Cycle Assess.* 2024, *29*, 218–239, doi: 10.1007/s11367-023-02245-y.

[28] Escribano, M.; Elghannam, A.; Mesias, F.J. Dairy Sheep Farms in Semi-Arid Rangelands: A Carbon Footprint Dilemma between Intensification and Land-Based Grazing. *Land Use Policy* 2020, *95*, https://doi.org/10.1016/j.landusepol.2020.104600.

[29] Zhou, Y.; Dong, H.; Xin, H.; Zhu, Z.; Huang, W.; Wang, Y. Carbon Footprint Assessment of a Large-Scale Pig Production System in Northern China: A Case Study. *Trans. ASABE* 2018, *61*, 1121–1131, doi: 10.13031/trans.12805.

[30] Arrieta, E.M.; González, A.D. Energy and Carbon Footprints of Chicken and Pork from Intensive Production Systems in Argentina. *Sci. Total Environ.* 2019, *673*, 20–28, doi: 10.1016/j.scitotenv.2019.04.002.

[31] Halloran, A.; Hanboonsong, Y.; Roos, N.; Bruun, S. Life Cycle Assessment of Cricket Farming in North-Eastern Thailand. *J. Clean. Prod.* 2017, *156*, 83–94, https://doi.org/10.1016/j.jclepro.2017.04.017.

[32] Dreyer, M.; Hörtenhuber, S.; Zollitsch, W.; Jäger, H.; Schaden, L.-M.; Gronauer, A.; Kral, I. Environmental Life Cycle Assessment of Yellow Mealworm (Tenebrio Molitor) Production for Human Consumption in Austria – a Comparison of Mealworm and Broiler as Protein Source. *Int. J. Life Cycle Assess.* 2021, *26*, 2232–2247, doi: 10.1007/s11367-021-01980-4.

[33] Pignagnoli, A.; Pignedoli, S.; Carpana, E.; Costa, C.; Dal Prà, A. Carbon Footprint of Honey in Different Beekeeping Systems. *Sustainability* 2021, *13*, 11063, doi: 10.3390/su131911063.

[34] Runesson, E. Compilation of life cycle assessments of cultivated blue mussels, [Online]. https://stud.epsilon.slu.se/16375/ (Accessed Date: November 23, 2024).

[35] Martini, A.; Calì, M.; Capoccioni, F.; Martinoli, M.; Pulcini, D.; Buttazzoni, L.; Moranduzzo, T.; Pirlo, G. Environmental Performance and Shell Formation-Related Carbon Flows for Mussel Farming Systems.

Sci. Total Environ. 2022, *831*, 154891, doi: 10.1016/j.scitotenv.2022.154891.

[36] Karapidakis, E.; Markaki, M.; Kikaki, A.; Yfanti, S.; Nikologiannis, M. Introduction of Electricity Storage and Photovoltaics for an Adequate Self-Sufficiency in Large Building Complexes. *WSEAS Transactions on Environment and Development,* 2024, *20*, 37–45, https://doi.org/10.37394/232015.2024.20.5.

[37] Imene, B.; Nouria, K. The Shift towards Renewable Energies and Its Role in Sustainable Development in Algeria. 2024, *20*, 940–953, doi: 10.37394/232015.2024.20.87.

[38] Ramos-Suárez, J.L.; Ritter, A.; Mata González, J.; Camacho Pérez, A. Biogas from Animal Manure: A Sustainable Energy Opportunity in the Canary Islands. *Renew. Sustain. Energy Rev.* 2019, *104*, 137–150, doi:10.1016/j.rser.2019.01.025.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed to the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.