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Ex Ante Emergy Synthesis of Cultivated Meat: Sustainability Insights and Benchmarks Against Conventional Systems †

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Abstract

Cultivated meat emerges as a promising alternative to conventional meat, the production of which causes significant environmental pressure, including greenhouse gas emissions, water demand, and pasture expansion, alongside ethical concerns related to animal slaughter. Life Cycle Assessments (LCAs) often highlight reductions in these impacts for cultivated meat, but they typically adopt a technocentric perspective, omitting flows of renewable natural resources and human labor. In this context, emergy (with an "m") environmental accounting offers a valuable methodological complement to LCA, incorporating biophysical and systemic perspectives for a more holistic analysis. The objective of this study is to apply emergy accounting to a cultivated meat production system. The results indicate that cultivated meat exhibits a Unit Emergy Value (UEV) of 0.43×10^{13} sej/kg-meat, which is up to 13 times lower than that of conventional meat, thereby indicating a higher emergy efficiency. However, it still depends heavily on economic resources (71.1% of the total emergy). As a result, it presents low emergy yield (EYR of 1.41), high environmental load (ELR of 6.97), low renewability (12.5%), and an emergy sustainability index (ESI) of 0.20 (ESI < 1 denotes unsustainability), thus indicating that the system is unsustainable at its current technological stage. Compared to conventional livestock systems, particularly extensive systems with greater integration of natural resources, cultivated meat presents one of the poorest emergy performances due to its highly artificial energy and material basis, which is dependent on non-renewable resource inputs. These findings contrast with the optimistic conclusions from LCA studies, emphasizing the inferiority of cultivated meat in emergy terms and the need for complementary approaches to generate broader diagnostics. The analysis also identifies optimization opportunities, such as resource input substitution and the integration of renewables, aiming for greater sustainability in protein production.

Keywords: biophysical sustainability; cultivated meat; emergy; environmental efficiency; LCA

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1. Introduction

The global population is projected to reach 10 billion by 2050, an increase of approximately 2 billion people from 2012. To sustain this growing population, alongside other material and energy needs, the issue of food security demands special attention. In this

context, cultivated meat has been proposed as a strategic alternative to meet the demand for animal protein, particularly considering the environmental pressure exerted by conventional livestock farming [1]. Cultivated meat, also known as in vitro meat, is a food product obtained through the laboratory cultivation of animal cells. The biotechnological processes for producing cultivated meat involve the isolation and proliferation of stem cells in bioreactors under controlled conditions, aiming to mimic the formation of animal muscle tissue and fat. Although the goal is to create a food product with sensory and nutritional characteristics similar to conventional meat to facilitate its substitution, challenges such as consumer acceptance must be overcome for its widespread adoption. For instance, Quevedo-Silva and Pereira [2] concluded that food neophobia and perceptions of artificiality are central barriers. Similarly, Fu et al. [3] indicated that consumer physical health, animal welfare, and the sensory and nutritional quality of the food promote the acceptance of cultivated meat, whereas technological neophobia inhibits it. Furthermore, Pasca and Arcese [4] emphasize that job losses in the agri-food supply chain and the end of culinary traditions represent additional socioeconomic obstacles.

Conventionally produced animal meat supplies nearly the entire market for meat protein. However, conventional livestock farming such as beef cattle ranching is recognized as one of the anthropogenic activities with the highest greenhouse gas (GHG) emissions, in addition to its extensive use of finite resources such as land and water [5,6]; according to Pallaoro et al. [1], livestock activities account for approximately 14% of total global anthropogenic emissions. Other impacts associated with conventional meat production include fertile soil degradation, excessive water consumption, pollution of water resources, biodiversity loss from deforestation, and the intensive use of agrochemicals on pastures and in feed production [6–8]. For Scheffer et al. [5], given the growing need for protein-rich foods—particularly animal meat—and the environmental problems related to conventional production, cultivated meat emerges as a potential alternative with lower environmental impacts. Cultivated meat may offer a range of advantages and potential benefits compared to conventional production, among which, according to Sinke et al. [9], the reduction in pasture area is perhaps the most pronounced. This challenges conventional meat in a global scenario of increasing demand for grazing land and decreasing available arable land. It also includes the ethical aspects presented by Treich [10], who notes that cultivated meat represents a moral improvement over conventional meat and has the potential to revolutionize the industry.

Recent studies have utilized life cycle assessment (LCA) to evaluate the environmental performance of cultivated meat, often focusing on identifying and optimizing production hotspots. Among others, Tuomisto et al. [11] assessed different bioprocess designs, indicating that the greatest impact reductions were achieved by optimizing cell metabolism (64–67% reduction) and using renewable energy sources. From a dietary perspective, Mazac et al. [12] modeled the inclusion of cultivated meat in Danish diets and found it could lead to national emission decreases of up to 21%, a climate impact reduction nearly as substantial as a fully vegan diet, although at a higher consumer cost. Kim et al. [13] evaluated a novel cultivated meat burger, which showed an 87% reduction in greenhouse gas emissions, 90% less land use, and 96% less water use compared to a conventional beef patty. Focusing on the medium of cultivation for cell growth, Nikkhah et al. [14] found that rapeseed protein-based medium reduced global warming potential fivefold compared to recombinant albumin formulations, highlighting recombinant proteins as key hotspots; Trinidad et al. [15] concluded that recombinant growth factors like IGF-1 dominate environmental impacts in cultivated meat production, with 1 mg generating 0.1 kg CO_2eq. due to their energy-intensive synthesis; Wali et al. [16] showed that replacing fetal bovine serum with egg-white protein hydrolysates cuts medium global warming potential by 81% while

lowering other impacts. In general, these LCAs indicate that cultivated meat can offer environmental benefits over conventional meat, with major reductions in greenhouse gas emissions, land use, and water consumption.

Although many conclusions have been reached regarding the superior environmental performance of cultivated meat compared to conventional meat, it is important to note that most authors have utilized the Life Cycle Assessment (LCA; [17,18]) method. This method can be considered technocentric, as it does not account for, from a systemic and broadened perspective, the labor and natural resources required to support the production process. In this regard, while acknowledging that LCA provides valuable information on the downstream impacts of production systems, it is essential to consider complementary approaches. To this end, emergy accounting (spelled with an 'm'; Odum [19]) offers a powerful complementary approach. It fundamentally shifts the analytical focus from the downstream impacts of a system's outputs, typical of LCA, to the upstream dependencies on its inputs. This is achieved by adopting a donor-side perspective to quantify the 'real wealth' invested by the biosphere, essentially measuring nature's 'effort' in providing resources and sustaining production. Additionally, this biophysical method successfully integrates the value of both natural resources and human labor into a common unit. Perhaps its most significant advantage, which sets it apart from alternative approaches, is its recognition that different forms of energy have different qualities or abilities to do work. Consequently, emergy accounting would complement the LCA findings rather than substituting them, providing a more holistic understanding of a system's reliance on nature and contributing key insights from a different, top–down perspective.

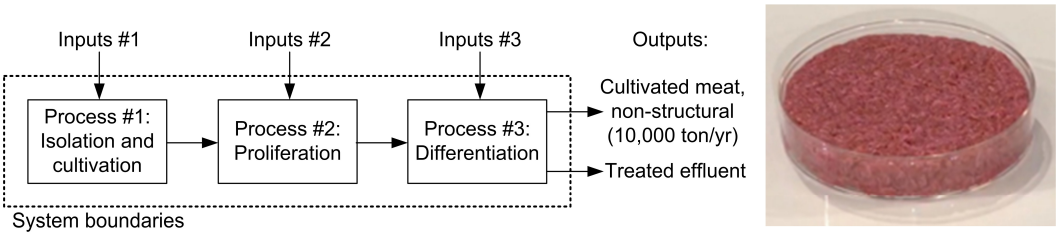
In the field of livestock production, emergy accounting has been applied in several studies. For example, Amiri et al. [20] assessed three beef cattle production systems in Iran, indicating that the semi-intensive system for the native Sistani breed was more efficient and reliable than others. Similarly, Alfaro-Arguello et al. [21] used an emergy-based approach to compare holistic and conventional ranching in Mexico, concluding that holistic ranches exhibited double the sustainability performance and a 25% higher emergy yield ratio without compromising productivity. The sustainability of grazing systems was also the focus of Rótolo et al. [22], who evaluated cattle grazing in the Pampas region of Argentina. The authors found the system to be environmentally sustainable and noted that natural pastures showed the highest sustainability due to a low dependence on purchased inputs. Finally, Reis et al. [23] applied emergy accounting and economic analysis to integrated crop–livestock systems versus continuous cropping and livestock systems in Brazil. The integrated system balanced emergy and economic performance (ESI = 0.66; 235 USD/ha), unlike the cropping system, which had high profitability but a greater environmental load (ESI = 0.47; 295 USD/ha), and the livestock system, which had low performance in both. However, to date, no emergy study on cultivated meat production has been identified in our literature review, which limits more in-depth discussions between the results of LCA and emergy. At this point, the following research question is raised: Would cultivated meat production exert lower pressure on the environment compared to conventional meat production from the perspective of emergy environmental accounting?

This work aims to apply emergy environmental accounting to an ex ante cultivated meat production system. It is expected to contribute to a more holistic view beyond LCA in discussions about the environmental performance of this new form of animal protein production, providing improved support for decisions and guidance for future work seeking to enhance its environmental performance.

2. Materials and Methods

2.1. Modeling the Cultivated Meat Production System

In this study, the industrial-scale production of 10,000 tons per year of cultivated meat is modeled as illustrated in Figure 1. The study aims to evaluate the emergy performance of this production system and compare it with conventional meat production alternatives reported in the literature. The system boundary (spatial window) considered is 'gate-to-gate', exclusively encompassing the industrial operations within the facility. All input and output flows are accounted for within a one-year temporal window. Broadly, the production process as diagrammed in Figure 1a is divided into three sequential industrial processes: #1—cell isolation and initial cultivation; #2—cell proliferation; and #3—cell differentiation into muscle tissue. The main output of the system is cultivated meat (unstructured biomass) ready for consumption as exemplified in Figure 1b, at a quantity of 10,000 tons per year, in addition to treated effluents. At the current technological stage of cultivated meat production, most available data in the literature refer to unstructured biomass, as the industry is still in its early developmental phases and there is limited technical knowledge on processes capable of generating structured products that resemble conventional meat cuts. Existing experimental systems focus primarily on cell proliferation and mass generation rather than on achieving organized tissue architectures. Consequently, unstructured biomass remains the most representative and well-documented output currently available for comparative analysis in emergy-based assessments. Future studies may consider emerging techniques such as 3D bioprinting for a final product more similar to regular steaks and with enhanced cost-effectiveness compared to unstructured biomass, as pointed out by Guo et al. [24].



(**a**) (**b**)

Figure 1. A general view of the case studied. (**a**) An overview of the boundaries of the evaluated cultivated meat production system, including its three main internal industrial processes. (**b**) Presentation of the world's first cultured hamburger (unfried). Image credit: World Economic Forum [25]. Licensed under CC BY 3.0. Source: Wikimedia Commons.

The data for modeling were extracted from the study by Sinke et al. [9]; therefore, they constitute secondary data. As this is an innovative yet immature production system, which also involves uncertainties and industrial secrets, obtaining primary data has not been possible to date. Nonetheless, Sinke et al. [9] modeled an ex ante cultivated meat production system (projected for 2030) based on several scientific references, and subsequently applied a life cycle assessment to discuss its environmental performance. This model was designed to be generic, serving as a reference for various types of meat (beef, pork, poultry, fish). It is assumed that the particularities of each type (e.g., stem cell type, differentiation time) do not markedly affect the mass and energy flows within the scope of this analysis. The system adopts a hybrid production approach: the proliferation phase occurs in batches (with periodic changes in the culture medium), while the differentiation phase employs a perfusion system (with continuous removal of the exhausted medium). This arrangement allows for more precise control of the cellular environment, which is essential for maintaining the high viability and yield of the process.

The modeling reflects a technology under development, not yet optimized for full industrial scale. Consequently, the production demands high-purity inputs, such as amino acids, glucose, vitamins, and growth factors with a purity grade compatible with the good manufacturing practices (GMPs) of the pharmaceutical industry. This requirement, coupled with technological immaturity, likely results in operational inefficiencies and a high consumption of energy and materials per unit of product. These characteristics may increase and/or overestimate the emergy flows (in sej) associated with the various subsystems and the cultivated meat system as a whole. This underscores the importance of an uncertainty analysis, as presented in a subsequent section. On the other hand, it is important to emphasize that the data considered in the modeling are the most current and detailed available.

2.2. Emergy Accounting

Emergy accounting is an environmental assessment method grounded in thermodynamics and systems theory that quantifies the environmental work previously required, both directly and indirectly, to make a product or service [19]. Unlike conventional economic approaches, which attribute value from the receiver's perspective, emergy adopts the donor's perspective, expressing the biophysical value in terms of the available energy of a single type used to generate a given good. This embodied energy is expressed in solar emjoules (sej), whose main feature is the ability to compare natural and economic resources on a common physical basis. Emergy also recognizes the 'quality' or hierarchy of energy, represented by the Unit Emergy Value (UEV), which reflects higher capacity to organize, control, and amplify energy flows in the energy hierarchy. The higher the emergy invested in something, the higher its energy quality will be.

The synthetic application of emergy accounting, often referred to as emergy synthesis, involves three main stages as follows:

(1) First, system modeling is carried out by drawing an energy diagram that graphically represents all energy and material flows crossing the system boundaries, as well as internal processes and their connections, and the outputs, including the main product and co-products. For modeling, the symbols from Figure 2, based on the energy systems language as proposed by Odum [19], are considered, respecting their meanings and purposes.

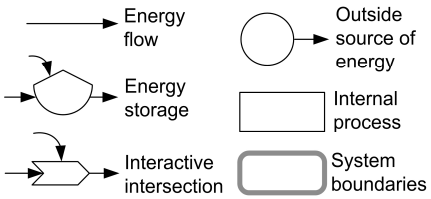


Figure 2. Symbols of the energy systems language used in this study. Based on [19].

(2) In the second stage, an emergy accounting table is prepared. In this table, each flow identified in the energy diagram is quantified in its original units (e.g., energy, mass, currency, labor hours) and then converted into emergy flows (in sej units) by multiplying them by their corresponding UEVs. The UEVs adopted in this study were mostly obtained from the scientific literature, and they exclude labor and services (indirect labor). When necessary, UEVs were estimated accordingly and are presented in the calculation details. To ensure methodological consistency, the UEVs used in this study are standardized to the global emergy baseline of 12×10^{24} seJ/yr [26]. After converting the input flows from their original units into emergy flows (sej), they are grouped into three categories: (i) R, local renewable resources from nature (e.g.,

sunlight, wind, rainfall, and vegetal biomass); (ii) N, local non-renewable resources from nature (e.g., mineral stocks, soil loss, and fossil fuels); and (iii) F, imported resources from the economy (e.g., grid electricity, processed materials such as steel, copper, plastics, and human labor). The sum of all these emergy flows represents the total emergy (or yield, Y) demanded by the system: Y = R + N + F.

(3) Finally, in the third stage, emergy-based performance indicators are calculated from the R, N, and F emergy categories to synthesize the system's emergy performance and facilitate discussion. Table 1 shows the emergy indicators considered in this study, along with their descriptions and algebraic expressions. All indicators are calculated for the evaluated cultivated meat production system. For comparison purposes, the same emergy-based indicators for traditional meat production were obtained from diverse studies in the literature.

Table 1. Emergy indicators used in this study.

Indicator	Unit	Description	Algebra
Unit Emergy Value (UEV)	sej/unit	Measures the total emergy required per unit of product. It indicates efficiency (input/output ratio) and energy 'quality', in the sense of organization power and influence.	UEV = Y/output
Renewability (%R)	%	Percentage of the total emergy derived from renewable sources.	%R = (R/Y) × 100
Emergy Yield Ratio (EYR)	dim.	The system's ability to amplify local resources, making R and N resources available to society. EYR < 2 usually indicates strong dependency on external resources and limited contribution to the broader economy.	EYR = Y/F
Emergy Investment Ratio (EIR)	dim.	Measures the economic resources required for each sej invested from natural resources (R + N). Lower values denote better performance, indicating systems that demand comparatively fewer resources from the economy.	EIR = F/(R + N)
Environmental Loading Ratio (ELR)	dim.	The environmental stress imposed by a system. Usually, ELR < 2 indicates low load, 2–10 moderate load, and >10 high load on the environment.	ELR = (N + F)/R
Emergy Sustainability Index (ESI)	dim.	Contribution of a system to the economy per unit of environmental load. ESI < 1 denotes unsustainability, 1–5 suggests short-term sustainability, and >5 indicates long-term sustainable performance.	ESI = EYR/ELR

Emergy indicators based on Brown and Ulgiati [27,28]. Legend: sej = solar emjoules; dim. = dimensionless; Y = total emergy demanded; R = renewable resources from nature; N = non-renewable resources from nature; F = resources from the larger economy.

2.3. Uncertainty Analysis

Due to inherent uncertainties in the inventory data and unit emergy values (UEVs), a stochastic Monte Carlo simulation approach was employed to quantify the variability of emergy indicators and assess the robustness of the results. A similar approach in an emergy study was presented by Agostinho et al. [29], confirming its practicality and effectiveness compared to other possible analytical approaches available for uncertainty calculation.

Uncertainty ranges were assigned differentially based on data source and type, focusing on the quantification of parameter uncertainties. For primary data sourced directly from Sinke's et al. [9], no uncertainty was applied (±0%), as these represented direct measurements, although secondary data. When raw data required modeling or were derived from different literature sources, an uncertainty range of ±20% was assigned to account for potential variability in data interpretation and inter-study differences. Similarly, for

UEVs, literature-based values were varied within ±10%, reflecting typical variation across published emergy studies. UEVs that were estimated in this study were assigned a wider uncertainty range of ±30% to account for greater potential variability in their derivation. Within each Monte Carlo iteration, parameter values were randomly sampled from normal probability distributions centered on the mean values, with bounds defined by the specified uncertainty ranges. A total of 10,000 iterations were conducted to ensure adequate convergence and a robust statistical representation of the parameter space. For reporting of the final results, the 95% confidence interval was used, providing a range encompassing the central 95% of the distribution and representing the upper and lower bounds of emergy indicator values with high confidence.

The uncertainty analysis calculations were performed with the assistance of the artificial intelligence model ChatGPT-5.1 [30] to develop the Python 3.14 source code (Supplementary Materials, Section SD), which was subsequently executed in the IDLE environment. The input data consisted of the emergy accounting table containing all quantified flows in their respective units with associated uncertainty ranges (0–20%), along with the UEVs for each flow and their respective uncertainty ranges (10–30%). The Monte Carlo simulation generated an output Excel® file containing 10,000 simulated values for each of the three primary emergy flows (R, N, and F) as well as the corresponding emergy sustainability index (ESI) values for each iteration.

2.4. Approach to Results Analysis

The results are evaluated through two distinct approaches: (a) tabular format, and (b) graphical representation using the 'emergy ternary diagram'. In the tabular format, the sustainability indicators obtained from the emergy synthesis of cultivated meat are discussed comparatively with emergy values from the literature, which evaluated conventional (non-cultivated) meat production systems. Different cattle management practices are considered, ranging from extensive and integrated systems to intensive operations. The objective is to present a large overview of the emergy performance across diverse meat production systems, as previously studied by other researchers. Importantly, to ensure fair comparison and discussion, the emergy of the slaughterhouse (Supplementary Materials, Section SB) was included in the emergy flows of conventional meat obtained from the literature, thereby standardizing both cultivated and conventional meat with the same final product: meat ready for consumption.

In addition to comparing the emergy indicators of cultivated and traditional meat production in a tabular format, the discussion can be further enhanced through the use of an 'emergy ternary diagram' [31,32], a graphical tool that displays the relative proportions of the R, N, and F emergy flows in sej/kg-meat. The diagram allows the emergy profiles of different systems to be visualized simultaneously in a single triangular plot, where each vertex corresponds to 100% of one of the flows (R, N and F). Regions near the top vertex represent systems sustained primarily by R resources; those on the right side indicate a dependence on economic F inputs; and those on the left reflect systems dominated by non-renewable natural resources (N). The emergy ternary diagram provides various graphical approaches that support a more in-depth discussion among the compared systems, including emergy sustainability lines that delineate sustainability regions, sensitivity lines for assessing development patterns, and other useful tools to aid the interpretation of different aspects of the compared systems. Applied examples of the emergy ternary diagram that explain in detail all its embodied analysis tools can be found in Almeida et al. [33].

Finally, for a cluster analysis (Supplementary Materials, Section SE), ESI data from each meat production system are analyzed using a Python code developed with artificial intelligence model ChatGPT [30] assistance and executed in the IDLE environment. Cluster

analysis is performed employing the K-means algorithm combined with Ward hierarchical linkage to partition the production systems based on their ESI values. The optimal number of clusters is determined through visual inspection of the dendrogram and consideration of authors expertise, rather than relying solely on automated optimization criteria. Prior to clustering, all ESI data are standardized using z-score normalization to ensure appropriate scaling of the variable. This cluster approach enables the identification of production systems with comparable sustainability profiles and facilitates a comparative evaluation of cultivated meat production relative to conventional meat production methods.

3. Results and Discussion

3.1. The Energy Diagram

The energy diagram in Figure 3 represents the evaluated large-scale industrial system for cultivated meat production, highlighting the flows of energy, materials, and human labor that sustain all processes. The symbology of systems diagrams detailed in Odum [19] is used to illustrate the hierarchical organization of flows and the interdependence among the system's internal components. The system is composed of three main subprocesses, including the isolation and cultivation of stem cells, cell proliferation, and differentiation, all integrated by a series of resource inputs that mostly originate from the economy, such as electricity, culture medium, chemical inputs, and the stainless-steel infrastructure of the reactors.

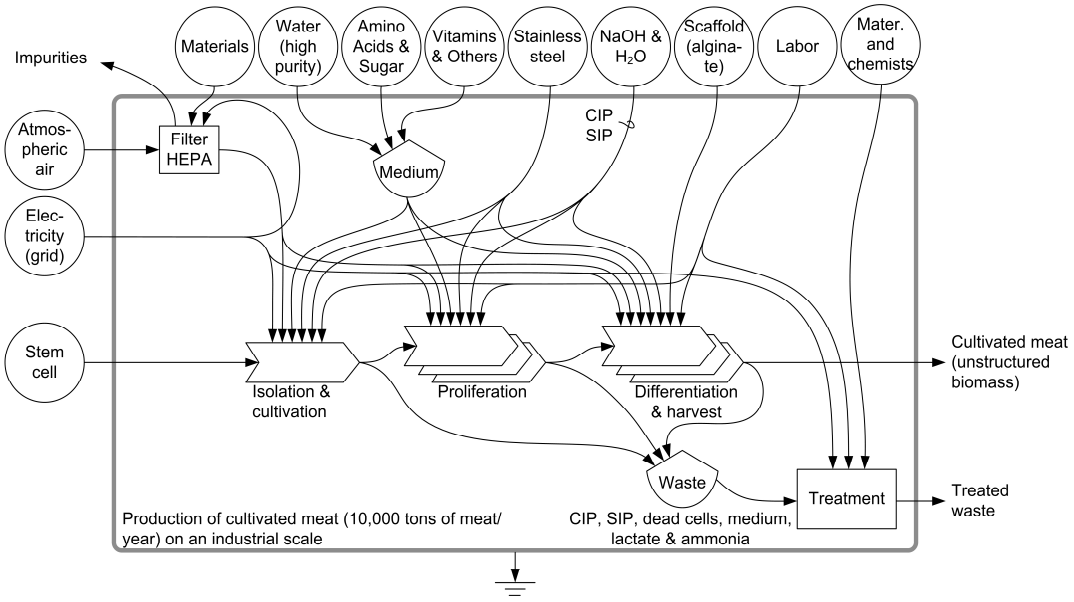


Figure 3. Energy diagram of the evaluated cultivated meat production.

Energy and material inputs come predominantly from the technosphere, with little direct participation from renewable resources of the biosphere. This includes the intensive use of electricity from the Brazilian grid, synthetic compounds for the culture medium, water and air purification processes, and environmental control that is highly dependent on equipment and industrial maintenance. Human labor appears as a specialized input (i.e., individuals with PhDs and technicians), responsible for the operation and quality control of the automated processes, while the main outputs of the system are cultivated meat (non-structural biomass) and treated waste before disposal. Regarding waste, the system generates ammonia and lactate, subproducts resulting from inefficiencies in the culture medium. Although these compounds could eventually be recovered as inputs within circular economy arrangements, in this study we adopted the treatment and disposal

approach modeled by Sinke et al. [9]. As the technology advances, these subproducts are expected to be either substantially reduced or separated for productive use, rather than treated and discarded as assumed here.

Overall, the diagram in Figure 3 highlights the artificial and energetically concentrated characteristic of cultivated meat production. The replacement of natural ecological functions (which exist in conventional meat production, such as pastures, solar radiation, rain, and fertile soil) with technological infrastructure suggests a production system with a low degree of renewability and a high dependence on external flows from the economy. This structure, viewed systemically, reinforces the technosystemic nature of the process, as it involves an arrangement that replicates natural biology in a highly controlled and industrialized environment, where performance depends more on the efficiency of technical processes than on integration with renewable ecological flows. The production of cultivated meat operates within the domain of organic chemistry, distinct from inorganic chemistry in its handling of complex organic compounds such as biomolecules, nutrients, and cellular structures. These organic materials are inherently prone to unpredictable reactions, including enzymatic degradation, microbial contamination, and unintended metabolic pathways, necessitating rigorous control measures like sterile environments, precise temperature regulation, and continuous monitoring. This heightened demand for oversight and intervention amplifies the energy and resource inputs required, potentially reducing overall system efficiency by diverting a notable portion of the technospheric flows toward maintenance and error mitigation rather than productive biomass growth.

3.2. The Emergy Accounting Table

After understanding how the system operates, as presented in Figure 3, the flows of energy, materials, and human labor that sustain it are quantified and converted into emergy flows in the unit of solar emjoules (sej). Table 2 presents the emergy accounting table for the industrial cultivated meat production system modeled in this study. The results show that the contributions of local renewable resources from nature (R), local non-renewable resources from nature (N), and resources from the economy (F) differ substantially in magnitude. The R resources totaled 5.4×10^{18} sej/year, corresponding to 12.6% of the total system emergy. The N resources reached 7.0×10^{18} sej/year, equivalent to 16.4%, while the F resources, which represent economic inputs and processed materials, amounted to 30.7×10^{18} sej/year, corresponding to 71.1% of the total emergy. The total emergy of the system is 43.2×10^{18} sej/year. These results indicate a strong dependence on external inputs from the economy, a typical characteristic of complex biotechnological systems still in their technological consolidation phase. The low share of local renewable resources (R at 12.6%) suggests that the emergy sustainability of the system is limited, with the process being sustained mostly by flows from the economy and from energy and knowledge-intensive (information) industrial chains, which are characterized by a heavy dependence on non-renewable resources.

The analysis of the individual emergy flows in Table 2 shows that the system is dominated by a few components that most influence the total emergy. The five most representative flows are specialized labor (higher education), which combined reached 29.9% of the total emergy, the high-purity water used in the culture medium (27.4%), the amino acids of the culture medium (25.0%), labor (technical training; 6.6%), and total electricity (approximately 3%). Together, these flows account for about 92% of the system's total emergy, indicating that the majority of the emergy support is concentrated in components directly related to the cell cultivation process and the specialized technical knowledge required for operating the bioreactors and the production system as a whole. In this context, specialized labor plays a fundamental role, demanding precise controls

and highly qualified decision-making in organic chemistry, where complex reactions with organic compounds require continuous monitoring to prevent unintended deviations. This need increases the quantity and quality of the required labor, which operate with sensitive biological materials and dynamic processes. Although these studies assess systems that differ substantially from the one evaluated here, they provide useful magnitude references: Rodriguez et al. [34] and Kim et al. [35] reported that labor contributes approximately 44% and up to 28% of total emergy for coffee production in Colombia and rice production in South Korea, respectively. In any case, in pursuit of continuous improvement in the production system whilst focusing on the technical–material aspect, any enhancement in the efficiency of culture medium use (including high-purity water and amino acids) would result in substantial improvements in the overall emergy performance of the system.

Table 2. Emergy table of the industrial cultivated meat production system as modeled and evaluated in this study.

Note [a]	Item	Quantity	Unit /Year	UEV (sej/Unit)	Emergy (sej/Year)	Emergy (%; sej/sej)
Local Renewable Resources from Nature (R)						
1	Stem cell (protein base)—24% R	0.48	g	3.74×10^{11}	1.80×10^{11}	<0.0
2	Electricity—48% R	4.25×10^{12}	J	1.47×10^{5}	6.25×10^{17}	1.4
3	Atmospheric oxygen—100% R	1,529,052	m^3	5.04×10^{10}	7.71×10^{16}	0.2
4	Scaffold (alginate)—15.5% R	7.75×10^{4}	kg	3.00×10^{8}	2.33×10^{13}	<0.0
5.1	Labor (Higher education)—30% R	22.50	Person	1.72×10^{17}	3.87×10^{18}	9.0
5.2	Labor (Technical training)—30% R	22.50	Person	3.77×10^{16}	8.48×10^{17}	2.0
				Total resources R=	5.42×10^{18}	12.6
Local Non-renewable Resources from Nature (N)						
2	Electricity—21% N	1.86×10^{12}	J	1.47×10^{5}	2.74×10^{17}	0.6
4	Scaffold (alginate)—0.1% N	5.00×10^{2}	kg	3.00×10^{8}	1.50×10^{11}	<0.0
5.1	Labor (Higher education)—43.2% N	32.40	Person	1.72×10^{17}	5.57×10^{18}	12.9
5.2	Labor (Technical training)—43.2% N	32.40	Person	3.77×10^{16}	1.22×10^{18}	2.8
				Total resources N=	7.07×10^{18}	16.4
Resources from the Larger Economy (F)						
1	Stem cell (protein base)—76% F	1.52	g	3.74×10^{11}	5.68×10^{11}	<0.0
2	Electricity—31% F	2.75×10^{12}	J	1.47×10^{5}	4.04×10^{17}	0.9
4	Scaffold (alginate)—84.4% F	4.22×10^{5}	kg	3.00×10^{8}	1.27×10^{14}	<0.0
5.1	Labor (Higher education)—26.8% F	20.10	Person	1.72×10^{17}	3.46×10^{18}	8.0
5.2	Labor (Technical training)—26.8% F	20.10	Person	3.77×10^{16}	7.58×10^{17}	1.8
6.1	Stainless steel (filter)	6.00×10^{0}	kg	9.50×10^{12}	5.70×10^{13}	<0.0
6.2	Glass microfiber (filter)	7.50×10^{0}	kg	2.22×10^{12}	1.67×10^{13}	<0.0
7	High purity water (medium)	4.47×10^{8}	L	2.65×10^{10}	1.18×10^{19}	27.4
8.1	Amino acids (medium)	2.83×10^{6}	kg	3.81×10^{12}	1.08×10^{19}	25.0
8.2	Sugars (medium)	4.00×10^{6}	kg	5.30×10^{11}	2.12×10^{18}	4.9
9.1	Recombinant proteins (medium)	3.00×10^{4}	kg	1.87×10^{13}	5.61×10^{17}	1.3
9.2	Salts (medium)	2.24×10^{6}	kg	1.00×10^{9}	2.24×10^{15}	<0.0
9.3	Buffering agent ($NaHCO_3$) (medium)	2.60×10^{5}	kg	1.00×10^{9}	2.60×10^{14}	<0.0
9.4	Vitamins (medium)	2.00×10^{4}	kg	1.00×10^{12}	2.00×10^{16}	<0.0
9.5	Growth factors (medium)	1.00×10^{3}	kg	1.00×10^{11}	1.00×10^{14}	<0.0
10	Stainless steel (bioreactors)	3.12×10^{2}	kg	9.50×10^{12}	2.96×10^{15}	<0.0
11.1	Water	1.00×10^{9}	L	7.28×10^{8}	7.28×10^{17}	1.7
11.2	NaOH	1.00×10^{6}	kg	5.00×10^{9}	5.00×10^{15}	<0.0
12	Effluent treatment	1,447,210	m^3	2.51×10^{9}	3.63×10^{15}	<0.0
				Total resources F=	3.07×10^{19}	71.1
13	Cultivated meat (output)	1.00×10^{7}	kg	4.32×10^{12}	4.32×10^{19}	100

[a] The calculation report, which includes the data used to compile the inventory, modeling, and the sources of the UEVs, is available in the Supplementary Materials, Section SA.

3.3. Emergy-Based Performance Indicators

The third part of applying emergy environmental accounting involves the calculation of performance indicators. Table 3 presents the indicators for the evaluated cultivated meat system and provides comparisons with literature references on conventional meat production. This analysis compares a single cultivated meat system with 11 traditional systems from the literature, each operating under different management practices and energy intensities. Such comparison, considering the diversity of systems, provides a meaningful reference for understanding where cultivated meat stands relative to different positions along the energy hierarchy. No emergy studies on cultivated meat were found in the literature, only life cycle assessments and discussions of technological or ethical aspects, which underscores the originality of this work. To make the comparisons more equitable, adjustments were made to the literature data: (a) conversion of all R, N, and F emergy flows to the current standardized emergy baseline of 12×10^{24} sej/year; and (b) inclusion of the slaughterhouse stage in the comparative data, as the output of the cultivated meat system is meat ready for consumption, whereas the boundaries of traditional meat production studies typically cover production only up to the animal ready for slaughter. These adjustments strengthen the robustness of the comparative discussions.

Table 3. Emergy indicators of the cultivated meat evaluation system and traditional meat production systems.

Meat Production Systems	UEV ($\times 10^{13}$ sej/kg-Meat)	EYR (dim.)	%R (%)	EIR (dim.)	ELR (dim.)	ESI (dim.)
1. Cultivated meat, this study	0.43	1.41	12.5	2.46	6.97	0.20
2. Amiri et al. [20], Extensive, Iran	2.28	9.30	71.6	0.12	0.40	23.39
3. Amiri et al. [20], Semi-Intensive, Iran	1.63	1.68	40.5	1.47	1.47	1.14
4. Amiri et al. [20], Intensive, Iran	3.59	1.31	23.8	3.19	3.19	0.41
5. Alfaro-Arguello et al. [21], Conventional, all ranches, Mexico	2.11	1.47	27.3	2.11	2.67	0.55
6. Alfaro-Arguello et al. [21], Holistic, all ranches, Mexico	0.41	2.59	47.1	0.63	1.12	2.30
7. Rótolo et al. [22], Steers (complete cycle), Argentina	0.68	3.72	60.8	0.37	0.64	5.78
8. Fonseca et al. [36], Silvopastoral system, Portugal	2.03	1.70	39.4	1.44	1.54	1.10
9. Brandt-Williams [37], Beef (two steers/ha), USA	3.76	1.53	33.5	1.90	1.98	0.77
10. Reis et al. [23], Conventional system, Brazil	1.21	3.09	61.1	0.48	0.64	4.85
11. Reis et al. [23], Integrated Crop–Livestock–Forestry System, Brazil	1.52	1.45	27.8	2.23	2.59	0.56
12. Wu et al. [38]—Integrated production, China	2.46	1.33	23.5	3.02	3.25	0.41

All data on the R, N, and F emergy flows were obtained from the references and adjusted to the 12×10^{24} sej/year emergy baseline when necessary. The R, N, and F flows from the slaughterhouse (R = 2.90×10^{11} sej/kg-meat; N = 3.16×10^{11} sej/kg-meat; F = 2.36×10^{11} sej/kg-meat; Supplementary Materials, Section SB) were added to the R, N, and F flows obtained from the literature studies on conventional meat production. All emergy indicators were calculated according to the updated R, N, and F emergy flows as available in the Supplementary Materials, Section SC. Although the extensive system from Iran (item 2) presents EYR and ESI emergy indicators that differ markedly from the other systems, we decided to include this study in the comparisons. Legend: dim. = dimensionless.

It can be observed in Table 3 that the UEV of cultivated meat, at 0.43×10^{13} sej/kg-meat, is a value comparable to the most efficient of traditional systems (holistic system in Mexico, with 0.41×10^{13} sej/kg-meat), but shows better performance than all other meat

production systems, which range from 0.68 to 3.76 × 10^{13} sej/kg-meat. Although a lower UEV can be interpreted as a lower emergy investment per unit of product (i.e., higher efficiency), in the case of cultivated meat, this result reflects a substitution of complex natural flows with concentrated industrial inputs, which does not necessarily translate to a lower load on the environment. Unlike traditional systems, cultivated meat does not internalize ecosystem services (such as nutrient recycling, soil regeneration, and direct use of solar energy), which limits the interpretation of this indicator in isolation. In any case, it can be stated that, in principle, producing cultivated meat has a higher emergy efficiency than producing meat conventionally.

The EYR of cultivated meat (1.41) is the third lowest among all evaluated systems, approaching that of the integrated Chinese system (1.33) and similar to the integrated system in Brazil (1.45). This indicates that the cultivated meat system is heavily dependent on external inputs from the economy, resulting in a low net emergy yield for the local economy; that is, it mobilizes and makes available few R and N resources for society. More extensive systems, such as the extensive Iranian model (EYR = 9.30) and the Argentine full-cycle system (EYR = 3.72), show higher values, indicating a greater capacity to transform local natural resources (R and N) into a final product without strong dependence on economic–industrial support. This aspect is also reflected by the EIR indicator, where the EIR of cultivated meat (2.46) is the third highest compared to natural and extensive systems, reflecting a high input of economic resources relative to natural flows. The most efficient systems in this regard are the extensive ones (EIR = 0.12), the Argentine full-cycle system (0.37), and the conventional Brazilian system (0.48), in which the majority of the energy support comes from free environmental resources. Thus, the high EIR of cultivated meat reveals a strong dependence on resources from the economy (mostly non-renewable) and a low degree of biophysical self-sufficiency.

Of its total emergy, cultivated meat demands 12.5% from renewable resources, the lowest value in Table 3, evidencing the system's low renewability. In contrast, extensive and silvopastoral agricultural systems show a greater contribution from renewable flows: up to 71.6% in the extensive system of Iran and ~61% in the Argentine and Brazilian systems. This indicates that the cultivated meat evaluated in this study operates in a highly industrialized environment, dependent on electricity as an energy source, processed materials such as culture medium with synthetic nutrients, and technical knowledge (specialized labor), whereas traditional livestock systems mobilize local natural resources (solar energy, natural biomass, and ecosystem services) and require less specialized labor.

The ELR of cultivated meat (6.97) is the highest value among all analyzed systems, indicating a high environmental load. Extensive and integrated systems, such as that of Iran (ELR = 0.40) and the conventional Brazilian system (ELR = 0.64), operate with a much lower environmental load, since the energy base is predominantly from natural resources. This contrast reinforces that cultivated meat, although free from the direct use of pasture land and enteric methane emissions from live animals, transfers and amplifies the environmental load to the industrial and energy sectors that supply the production inputs.

Finally, the ESI of cultivated meat, at 0.20, is comparatively the lowest, indicating low emergy sustainability. ESI values below 1 indicate systems that are not environmentally sustainable, as they depend heavily on economic flows. In contrast, extensive and more ecologically based systems show much higher ESI values (reaching 23.39 in the extensive Iranian system and 5.78 in the Argentine system), indicating that emergy sustainability is strongly associated with the use of renewable resources and integration with local natural processes. As previously justified, due to the inherent uncertainties in the raw data and UEVs, a Monte Carlo analysis was applied to evaluate their impact on the final ESI value. The Supplementary Materials, Section SD, details the calculation, including the Python

code. The result indicates an ESI of 0.20 ± 0.06 (95% confidence interval) for the evaluated cultivated meat system. Notably, even with high uncertainty ranges (±10% to ±30%) for some parameters, the value remains aligned with the comparative discussions for ESI = 0.20, reinforcing the robustness of the analysis that the low emergy sustainability of cultivated meat stems from its high dependence on economic resources.

Although emergy indicators reveal a low biophysical sustainability for cultivated meat (ESI = 0.20), with a strong dependence on non-renewable economic resources, life cycle assessment (LCA) studies point to substantial environmental benefits for cultivated meat compared to conventional meat, as discussed in the review by Scheffer et al. [5]. Specifically, the studies by Sinke et al. [9] and Kim et al. [13] indicated that cultivated meat can demand substantially less land area (up to 99% less), emit less CO_2 equivalent (reductions of 78–96% in greenhouse gases), and consume less water (up to 82–96% less), especially in optimized scenarios with the use of renewable energies in the production system. This apparent discrepancy stems from the fundamental differences between LCA and emergy environmental accounting as assessment tools. While LCA quantifies environmental impacts from a more technocratic perspective, emergy adopts a systemic perspective, considering the quality of energy and the renewability of material and energy flows on a global biophysical scale, revealing hidden dependencies on concentrated industrial inputs. As discussed by Agostinho et al. [39], LCA and emergy are complementary, not competing, approaches. Integrating both allows for a more robust, multi-criteria diagnosis, avoiding misleading interpretations based on a single perspective, such as overestimating the sustainability of cultivated meat based solely on LCA metrics without considering its emergy performance, or vice versa.

3.4. The Emergy Ternary Diagram

The comparative assessment of the overall emergy performance of the systems can be observed in Figure 4. The analysis of the ternary diagram in Figure 4a reveals the extreme position of the cultivated meat system (point 1), locating it at the lower right vertex, which indicates a dependence on resources acquired from the economy (F); points 13 and 14 also represent cultivated meat, but considering the uncertainties of R, N, and F from the Monte Carlo analysis. In contrast, the contribution of local renewable (R) and non-renewable (N) resources is practically null, resulting in an Emergy Sustainability Index (ESI) markedly lower than 1 and classifying the system as unsustainable from an emergy perspective; this also occurs for points 4, 5, 9, 11, and 12. This profile contrasts with the analyzed conventional and integrated livestock production systems, which, despite their variability, indicate a greater dependence on local renewable resources (R), such as the solar energy that drives pastures and the potential energy of rainfall, among other resources. Several of these traditional systems fall into categories of short- to medium-term sustainability (1 < ESI < 5; points 3, 6, 8, and 10) or even long-term sustainability (ESI > 5; points 2 and 7), highlighting a more favorable resource balance. These results indicate that the current cultivated meat technology operates as a non-complex, linear, and external input-intensive system, distancing itself from the natural biogeochemical cycles that sustain agricultural systems. For cultivated meat to become a competitive alternative in terms of emergy sustainability, innovations focused on reducing the dependence on inputs from the economy (F) and integrating renewable energy sources (R) into the process would be important. For example, according to Table 2, this could be achieved mainly through the efficient recycling of the culture medium (which would reduce the need for high-purity water and amino acids), or by using energy sources considered more renewable, such as local photovoltaics.

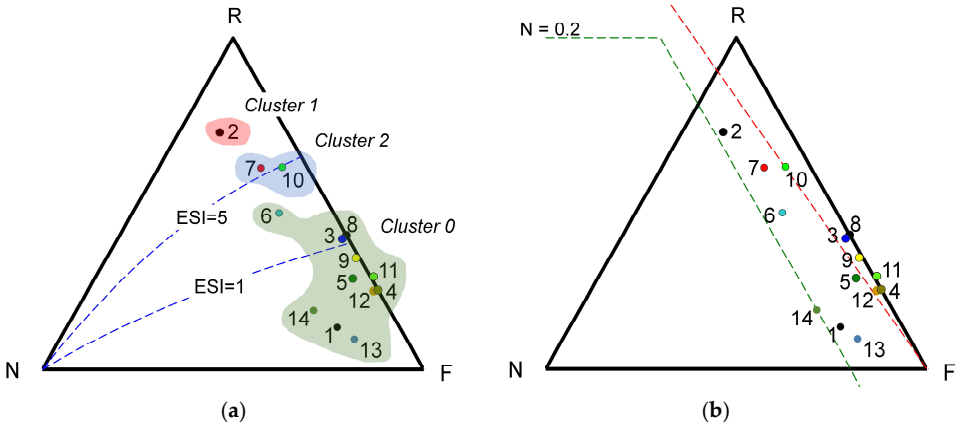


Figure 4. A ternary emergy diagram showing the emergy overall performance of the cultivated meat (point 1) and its range including uncertainties as represented by points 13 and 14. All other points (2–12) correspond to conventional meat production systems as described in Table 3. Figure (**a**) shows the emergy sustainability lines (ESI) of 1 and 5, in addition to the cluster groups based on the ESI (Supplementary Materials, Section SE), and figure (**b**) shows the sensitivity line (red) and the N resource line (green).

Still, regarding Figure 4a, the cluster analysis of ESI values revealed three distinct groupings among the twelve meat production systems examined. Cluster 0, comprising eleven systems (78% of the sample; including points 13 and 14, which are related to the uncertainties within cultivated meat point 1 with ESI = 0.20 ± 0.06), was characterized by low ESI values with a mean of 0.83, indicating systems with high dependence on non-renewable resources. This cluster included the cultivated meat system from this study (ESI = 0.20), along with conventional and semi-intensive meat production methods from Iran, Mexico, Portugal, USA, Brazil, and China. The similarity in sustainability profiles among these diverse geographic and management contexts suggests that both conventional meat production and the cultivated meat system analyzed share comparable levels of emergy dependency on external, non-renewable inputs. This finding indicates that the cultivated meat technology evaluated does not present a clear sustainability advantage over conventional meat systems in terms of emergy sustainability, despite potential benefits in other environmental dimensions such as land use, water consumption, or even greenhouse gas emissions, as discussed by Scheffer et al. [5], Risner et al. [6], and Pallaoro et al. [1]. Cluster 1 contained only the extensive meat production system from Iran (point 2; ESI = 23.39), representing a potential outlier with exceptionally high emergy sustainability. This system's superior sustainability profile likely reflects its dependence on pasture-based production with minimal external energy inputs, demonstrating that extensive, low-input grazing systems can achieve markedly higher sustainability indices compared to industrial production methods. Cluster 2 grouped two systems with moderate ESI values (mean = 5.32): the complete-cycle steer production from Argentina (point 7; ESI = 5.78) and the conventional meat system from Brazil (point 10; ESI = 4.85). These systems exhibited intermediate sustainability profiles, suggesting some balance between renewable and non-renewable resource utilization, though still substantially lower than the extensive Iranian system. These results indicate that enhancing emergy sustainability in meat production demands either a shift to extensive, low-input systems or major technological advancements that minimize non-renewable resource use, aiming for the efficiency of point 2. For cultivated meat to emerge as a viable sustainable alternative, it must achieve breakthroughs in energy efficiency and reduced reliance on external inputs to rival or surpass the profiles of pasture-based, low-input systems.

From Figure 4b, two other characteristics of meat production systems, whether cultivated or traditional, can be observed. The first relates to the maximum of 20% dependence on local non-renewable resources from nature (N) for these systems (green line). This implies that a sensitivity analysis aimed at improving system performance should focus on increasing R and decreasing F, as these actions would result in more effective changes than focusing on the reduction in N. Another interesting characteristic refers to the sensitivity line (red line), which shows that meat production systems 3, 4, 5, 8, 10, 11, and 12 have, on average, the same ratio of R to N resources of ~9.3/1 (using the conventional system in Brazil from point 10 as a reference). This implies that although the absolute values of the R, N, and F flows for these systems may vary greatly, their R/N flow ratio is similar. In other words, regardless of the scale, management, or production type of the meat systems analyzed, there is an intrinsic proportion or a common technological and/or ecological pattern in how they depend on local renewable resources (R) relative to local non-renewable resources (N). This constancy of the R/N ratio at 9.3 indicates a fundamental structural characteristic inherent to these systems: a common operational limit in how natural resources are integrated into the studied meat production systems, irrespective of their individual sizes. Although this characteristic is observed for most of the compared systems, it is not found in cultivated meat (point 1, including 13 and 14 with their uncertainties), nor in traditional meat systems 2, 6, and 7.

4. Limitations and Suggestions for Future Work

The results of this study highlight the potential of emergy accounting to assess the sustainability of emerging technologies like cultivated meat, but they also reveal inherent limitations in the current approach, especially due to the reliance on secondary data and the immaturity of the technology. To advance this field, future research should prioritize the collection of primary data from pilot or commercial facilities, overcoming the industrial secrets that currently restrict more precise analyses. This would allow for more robust modeling, incorporating specific variations by meat type (beef, pork, or poultry) and production scales, such as larger-volume bioreactors or advanced automation processes.

Another suggestion pertains to the optimization analyses of technical aspects, such as the chemical reactions in bioreactors, aimed at reducing the dependence on non-renewable emergy flows from the economy (F), which dominate about 70% of the total emergy in the evaluated system. For example, innovations in the culture medium, such as the development of recyclable formulations or those based on renewable agricultural byproducts as discussed by Wali et al. [16] and Nikkhah et al. [14], could decrease the consumption of high-purity water (currently accounting for 27.4% of total emergy) and synthetic amino acids (25.0%). In parallel, improvements in culture medium composition could also support the substitution of recombinant proteins, which have been identified as LCA hotspots by Trinidad et al. [15]. Furthermore, integrating local renewable sources, such as solar photovoltaic energy or biogas from organic waste (as suggested by Tuomisto et al. [11]), could increase the contribution of local renewable resources (R). Lastly, despite the social importance of generating employment, a reduction in labor (36.0% of total emergy) through increased technology for monitoring and production control via Artificial Intelligence (aligned with bioprocess optimizations as suggested by Tuomisto et al. [11]) could help to increase the ESI of cultivated meat; however, caution is warranted, as a portion of this labor contributes to R flows, which positively impact the ESI. As cultivated meat technology matures (as projected in dietary modeling for 2050 according to Mazac et al. [12]) and more data become available, sensitivity analyses and improvement scenarios can precisely identify where to implement actions. In any case, studies based on alternative scenarios

should be grounded in realistic data as emphasized and applied by Kim et al. [13], avoiding assumptions seen in initial hotspot assessments.

Although still somewhat distant from the current early stage of cultivated meat development, expanded assessments are suggested that include complete production and consumption chains, incorporating post-production impacts such as distribution and consumption. Implementing the cultivated meat production plant under the concept of local production arrangements, for instance, near the raw materials used for culture medium or energy sources, could result in greater emergy sustainability. This is based on the fact that transportation stages would not be as necessary, and the renewability of resources would be higher as they would be co-products from other production systems, thereby increasing R emergy flows and reducing F flows. Although still in the initial stages, efforts in this direction are already being made, such as in the study by Kim et al. [40] that found an economically and eco-friendly scaffold based on soy proteins.

Finally, interdisciplinary research combining emergy accounting with life cycle assessment (LCA) and economic analyses would help quantify trade-offs between environmental and economic aspects. As highlighted by Mateti et al. [41], the main current challenges for large-scale industrial production of cultivated meat include high production costs and limited public acceptance. These efforts would allow for the identification of optimized options that maximize overall performance, providing support for decision-makers and promoting more resilient and environmentally balanced protein production.

5. Conclusions

The application of emergy environmental accounting to the evaluated cultivated meat production system indicates that, although it has a Unit Emergy Value (UEV) of 0.43×10^{13} sej/kg-meat (an efficiency between 1.3 and 13 times higher than that of conventionally obtained meat), the cultivated meat system obtained an Emergy Sustainability Index (ESI) of 0.20 ± 0.06 (95% confidence interval), classifying it as unsustainable. This result reflects the high dependence on inputs from the economy (71.1% of total emergy) and a low renewability index (%R) of only 12.6%. This positions cultivated meat, in its current technological stage, as a product of high technological value but with limited biophysical sustainability performance.

From a comparative viewpoint, the emergy ternary diagram reveals that the current technology for cultivated meat offers no clear emergy sustainability advantage over traditional systems, approaching the worst performances observed in intensive conventional meat production. Although it may present potential advantages regarding land use, water demand, greenhouse gas emissions, biosecurity, and animal welfare, as well as other potential benefits from a life cycle assessment perspective (as reported in the scientific literature), its emergy performance is compromised by its intensive and artificial energy and material base. In contrast, extensive, silvopastoral, or integrated agricultural systems, being closer to natural ecosystems, exhibit a greater proportion of renewable resource use, lower Environmental Loading Ratios (ELRs), and consequently, higher emergy sustainability (ranging from 0.4 to 23). These results reinforce the importance of integrating animal production with natural ecosystems for the resilience of protein-based food systems.

In terms of implications for the global food transition, the results suggest that without substantial advances, such as a reduction of about 60% in F flows to raise the ESI to 1, cultivated meat could drive energy inequalities between regions and nations, favoring advanced industrialized economies over more rural systems found in developing countries. Public policies and technological incentives should prioritize hybridizations, aligning production with the UN's Sustainable Development Goals, notably SDG 2 (Zero Hunger) and SDG 13 (Climate Action). Furthermore, to avoid misplaced optimism, it is recommended

to integrate emergy accounting with life cycle assessments (LCAs) and economic evaluations, providing a holistic diagnosis that captures both specific impacts and large-scale biophysical dependencies, thereby guiding more resilient and equitable innovations for more effective decisions.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su18041807/s1, [42–50], Figure SA1: Three-arm emergy diagram of the production of high-genetic-value bulls that provide stem cell biomass used for the production of cultured meat; Figure SA2: Three-arm emergy diagram of the production of electrical energy from a hydraulic source; Figure SA3: Three-arm emergy diagram of the production of the red alga *Kappaphycus alvarezii* in Brazil; Figure SB1: Energy diagram of the conventional meat processing plant. Based on Costa [43]; Table SA1: Calculation of the UEV to produce 1 g of glass fiber; Table SA2: Calculation of the UEV to produce 1 L of high-purity water; Table SA3: Calculation of the UEV to produce 1 kg of amino acids; Table SA4: Calculation of the UEV to produce 1 kg of glucose; Table SA5: Calculation of the UEV to produce 1 kg of recombinant protein; Table SB1: Equipment inventory, their weights, and main materials for a meat processing plant with a capacity of 3,000,000 kg of meat/month. Source: Equipment list based on Costa [43]. Weights and Materials estimated; Table SC1: Emergy indicators for the evaluated cultured meat system and traditional meat production systems.

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