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The Environmental Impacts of Cultured Meat Production: A Systematic Literature Review

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Abstract. This paper provides an overview of the current state-of-knowledge surrounding the environmental impacts of cultured meat (CM) production. Adopting a systematic literature review (SLR) protocol, over 1,000 papers were retrieved and subsequently appraised through a defined collection of relevance- and quality-based inclusion and exclusion criteria. Utilising life cycle assessment (LCA) literature data, four key LCA impact categories were assessed: Land use (crop-eq m^2a/kg); Water consumption (L/kg); Energy requirements (MJ/kg), and greenhouse gas (GHG) production (kg CO_2-eq/kg). The results indicate that to produce 1kg of animal meat, CM production systems could require significantly less land, water and energy resources than conventional meat production methods. Major reductions in GHG emissions are also projected, in comparison to conventionally farmed beef. For other meat types, such as pork and chicken, the GHG reduction potential of CM is less substantial and is highly dependent upon the use of renewable energy sources during production. The LCAs reviewed here provide vital insight into the environmental impacts of changing the way we make meat, showcasing what a transition from conventional, to cellular, agriculture could look like for Earth's land, water and climactic systems. The accelerated rate at which the CM industry is expanding and its biotechnological production processes evolving, calls for increased LCA study. By periodically reviewing and synthesising the available LCA data in SLRs, the industry and its stakeholders can gather insights into any problematic processes, ingredients, or equipment, leading to realisation of optimum environmental efficiency outcomes for producing meat using cellular agriculture technology.

Keywords: Life Cycle Assessment (LCA), Cultured Meat, Cellular Agriculture, Systematic Literature Review.

1 Introduction

Over a third of Earth's land surface is currently being utilised for food production [3]. When glacial and barren environments are removed from this calculation, the footprint of global agriculture rises significantly, occupying half of all 'habitable land' available on our planet [9]. Most of this habitable land is used to produce meat, milk and eggs. Comprised of pastureland, grazing areas, and land used to grow animal feed crops, animal agriculture presently occupies an estimated 78% of all agricultural land on Earth [1]. Furthermore, the production of meat, milk and eggs has been identified as a primary cause of global biodiversity loss and a core driver of anthropogenic climate change (ibid.). Humanity's meat consumption habits are therefore responsible for creating two of the Anthropocene's greatest challenges, making the creation of more efficient means of producing animal products critical if we are to sustainably feed Earth's growing population whilst retaining omnivorous diets.

Anthropogenic climate change, the so-called "defining crisis of our time" [18], necessitates attention from governments, academics, industries and consumers in the search for solutions to mitigate (and potentially reverse) global warming. Increased awareness of animal agriculture's 'foodprint', a concept defining the overall environmental impacts generated by particular foods [5], has highlighted the benefits of a widespread transition towards meat-free, or meat-reduced diets. Whilst the number of consumers adopting climate-friendly diets, for instance, veganism, vegetarianism, flexitarianism and climatarianism, has risen significantly over the past decade [2], humanity as a whole remains reluctant to remove animal products from our diets. This has necessitated the creation of innovative technologies capable of meeting the demand for meat whilst also mitigating its catastrophic impacts on Earth's natural environment. One such technology is cellular agriculture.

Cellular agriculture applies a range of principles, processes and equipment to produce animal products from cell cultures. The industry is currently focused on animal products, creating meat, eggs and milk products, without the subsequent environmental, social, and ethical issues that are sometimes associated with rearing and slaughtering livestock. One of such products is cultured meat (CM), which is lab-grown meat.

Nevertheless, the consideration of scaling up of CM production is mostly confined to developed countries, where the legislation from governments is under development, e.g. the U.S. Food and Drugs Administration [19], the Food Standards Authority (FSA) in the UK [14] and the Food Standards Australia and New Zealand [4].

The environmental impacts associated with replacing conventional animal agriculture with cellular agriculture, can be measured through the Life Cycle Assessment (LCA) method. LCA can be used to quantify the ecological impacts of a product over its full life cycle, generally including raw material extraction, processing, manufacturing, distribution, and use [10]. The most common system boundaries used within LCA's are 'cradle-to-gate', 'cradle-to grave', 'gate-to-gate', and 'cradle-to-cradle'. Fig. 1 shows our depiction of a potential CM production system. It shows the components and processes of the CM production process that exist within a cradle-to-gate system boundary. As there are multiple cellular agriculture companies, working on a diverse range of CM products, with laboratories and production facilities dispersed across multiple geographical regions, this production process is anticipatory and may not be inclusive of all necessary inputs and stages. Additionally, the LCA methodology provides scope for studies to design completely unique system boundaries, which may exclude certain aspects of the production process entirely, creating further uncertainty.

The remainder of this paper is organized as follows. Section 2 shows the SLR steps followed in this research. Section 3 presents the key findings. Section 4 discusses the key results considering recent literature. Section 5 provides some conclusions, limitations and further research avenues.

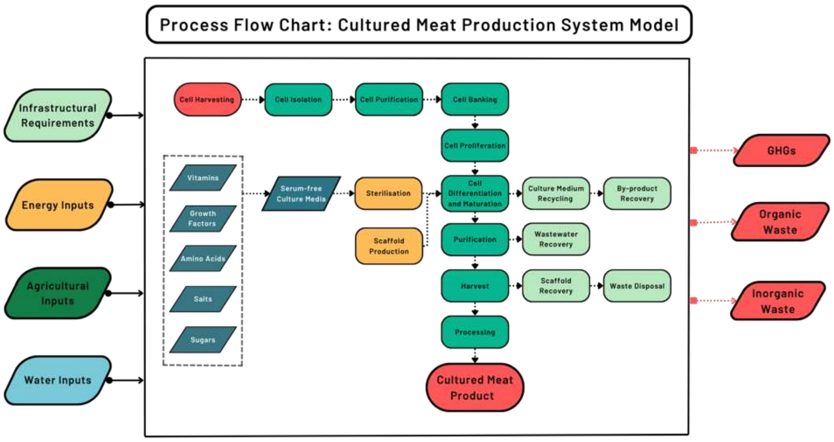

Fig. 1. Process Flow Chart: Cultured Meat Production System Model

2 Systematic Literature Review (SLR)

Through conducting a SLR of this field, the aim of this research is to provide a synthesis of the current state of knowledge on the environmental impacts of CM production and highlight gaps for future research.

2.1 Search strategy

The search for CM research was performed in March 2023 and limited to literature published post-2010. Searching the database Scopus using the following search string: 'TITLE-ABS-KEY ("cultured meat" OR "cultivated meat" OR "lab-grown meat")', highlights an increase from 2 to 212 in CM-related publications from 2010 to 2022.

For the SLR, five databases were utilised in the search: Scopus, Web of Science, ProQuest, Google Scholar and Science Direct. Research specifically focused on CM remains limited in most disciplines at present, however the field is expanding rapidly. A total of 9,253 CM-related publications were found that mention CM in some form. Most results, 7,160 of 9,253, were found on Google Scholar which did not have search refinement functionalities as advanced as the other databases utilised here. Subsequently, the Google Scholar search engine uncovered a substantial volume of research of low relevance to CM, including articles that only briefly or passively mention CM within text (i.e. general food sustainability articles), and also results from non-academic sources, including news articles, editorials, and blog posts. As this research solely concerns the LCA studies conducted on CM, the additional terms "Life Cycle Assessment" and "LCA" were added to the search string in each database to further refine the results. Refreshing the search strategy to target only the CM publications that meet the additional criteria of mentioning the LCA method within their title, abstract, keywords or main text, reduced the literature pool to 2,093 results across all databases. See *Fig. 2*.

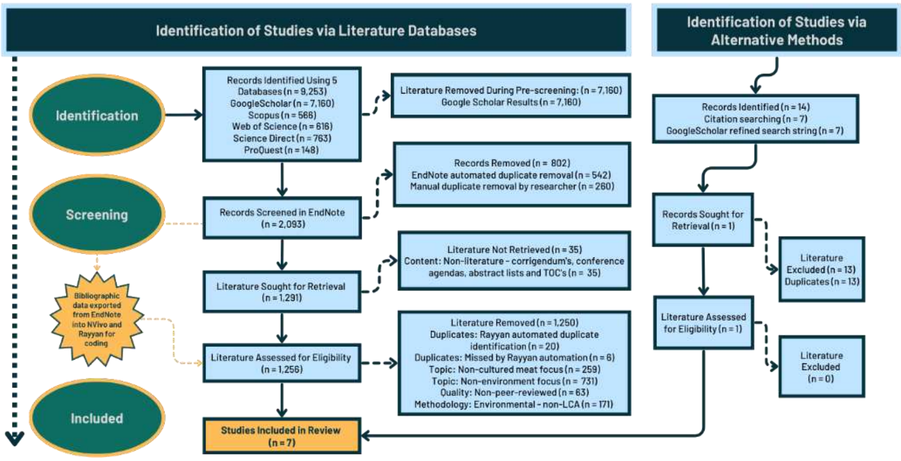

Fig. 2. Search strategy used in Systematic Literature Review of cultured meat (2010-2023)

2.2 Appraisal

The appraisal phase consisted of two primary steps. Firstly, refining the literature based on relevance to the research questions, and secondly, assessing the quality, credibility, methodological rigour and overall soundness of the relevant research. Results were input into the reference managing software EndNote to undergo this screening. After duplicates were removed, the abstracts of the remaining literature were analysed to determine their relevance to this study.

Literature that did not focus on the environmental impacts of CM was outside of the scope of this research and therefore excluded. Furthermore, literature that explored the environmental dimensions of CM but did not employ the LCA methodology were also excluded, however were kept for consultation and for contextual knowledge and additional insight. The inclusion criteria papers were assessed against for acceptance into final review are listed in Table 1.

In total, eight LCAs of CM were identified through this SLR process and one additional study [17] was discovered through backward and forward searching. To ensure all published LCAs of CM had been discovered through this SLR's methodological approach, the titles and authors of the eight papers were input into Litmaps online software to search for connected papers. No new results were found through Litmaps, confirming the robustness of this SLR's search strategy. The papers selected for full review are listed in Fig. 5. Seven of the eight CM LCAs were determined to have met the set inclusion criteria. The LCA conducted by [7] could not be included due to its focus on a plant-based-CM hybrid product, with CM comprising only 16.9% of its total mass.

Table 1. Systematic Literature Review inclusion and exclusion criteria

	Inclusion criteria	Exclusion criteria
Literature Type	Journal articles, book chapters, high quality grey and white literature	Magazines, newspapers, industry reports, poor quality grey and white literature
Date Range	Post: 1st January 2010 Pre: 10th March 2023 (Present)	Pre: 1st January 2010 Post: 10th Mar-2023 (Present)
Content	LCAs of cultured meat	Non- LCA, non-cultured meat, review papers
Quality	Peer-reviewed, methodologically sound, scientifically credible	Non-peer-reviewed, methodologically flawed, low scientific credibility
Language	English	Non-English (unless translatable)

2.3 Synthesis

The synthesis stage consisted of identifying, extracting and categorising the relevant data contained within the literature selected for inclusion. This data was selected and subsequently recorded in individual data collection sheets. The data synthesis sheet utilised here included sixteen criteria for information extraction, shown in Fig. 3 below.

Fig. 3. Criteria for information extraction

Employing SLR analysis and reporting, whereby each paper was assessed through an identical procedure, aided in reducing the potential for reviewer bias whilst also ensuring the development of a holistic and complete account of the literature field. This approach required the extraction of certain textual content of the included studies, for instance the LCA results, but also went beyond this to include the contextual, non-research dimensions of the publications, such as where and by who, CM LCA research is being published (institutions, author's countries, journals, etc.). Mapping the research landscape in this manner proved useful in identifying key research gaps and understudied topics within the literature, and the journals, institutions and researchers dominating this research field.

The data extraction sheets were uploaded to NVivo, along with a pdf of each full article, for content coding. NVivo software is typically utilized for qualitative data analysis but proved useful in this SLR as it allowed for the coding and visualization of numerous quantitative and qualitative features within the included papers. Utilising the data visualization features available on NVivo, maps of convergent and divergent factors between papers were generated which assisted with the identification of themes, for instance, which papers utilized a certain LCIA method (e.g., ReCiPe), and which papers analysed or excluded certain impact categories (e.g., which and how many papers included water usage in the assessment). After completing this process, the synthesized information was used for the SLR report write-up.

3 Findings

3.1 Cultured meat (CM) literature landscape

Fig.4 shows the distribution of CM literature on Scopus, segregated by research discipline and published from 2010 onwards. 7.1% (*N*= 87) of all research literature on CM between this date range has been categorized as Environmental Science.

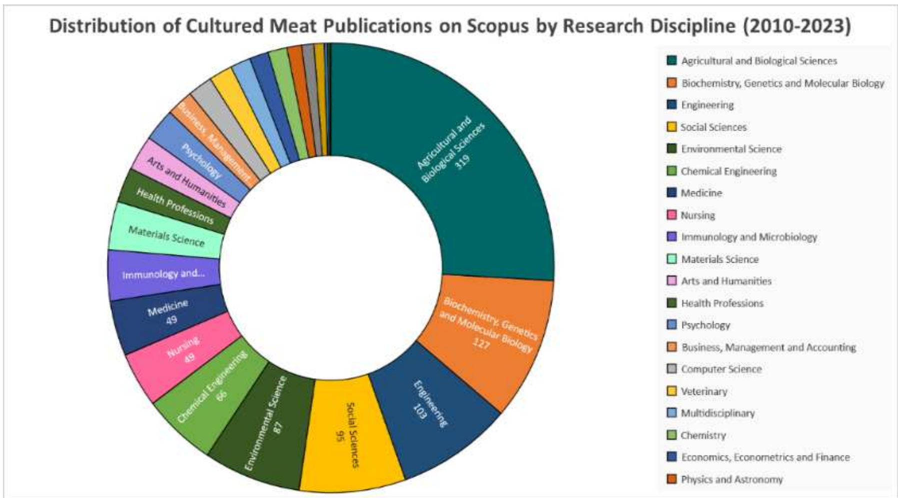

Fig. 4. Distribution of cultured meat publications on Scopus by research discipline (2010-23)

3.2 Life Cycle Analysis (LCA) studies of culture meat production

Fig. 5 presents the LCA results of the seven studies reviewed. The only conventional meat product [13] assessed CM against was poultry where they found CM to produce approximately five times more GHG's. [8] calculated that commercial-scale CM production would produce less GHG's than beef production but double those emitted for the same FU of conventional pork and triple the emissions of poultry. [11] however, calculated the carbon footprint of CM to be significantly lower than all forms of conventional meat production when sustainable energy is used during its production. If conventional energy is utilised within the CM facility, the meat produced has a lower GWP than beef but a slightly higher GWP than pork and poultry meat production. Whilst all studies agree that CM is likely to require less land than conventional meat production, discrepancies arise when comparing the Global Warming Potential (GWP) of CM calculated by each study. [16] reported GHG emissions for CM significantly lower than those from conventional beef, sheep, pork and poultry meat production, whilst [17] reported GHG emissions that remain significantly lower than those recorded for conventionally produced beef, sheep and pork, but are higher than those for poultry.

Study	Cell Culture Medium	Functional Unit (FU)	Key Findings (per kg)
Sinke, Swartz, Sanctorum, van der Giesen (2023)	Glucose, Soy Hydrolysate, Amino Acids from Microbial and Chemical Production, Microbial Recombinant Protein Production	1kg cultured meat product from land based animal with 20-30% dry matter content and 18-25% protein content	2.21-24.8 kg CO_2-eq/kg 116.48-481.70 MJ/kg 2.25-3.59 m2a crop-eq/kg 60-150 L/kg
Tuomisto, Allan and Ellis (2022)	DMEM and FBS (CMB and CMB128 scenarios) Essential 8™ (serum-free medium scenarios, CMC, SFB & SFE)	1kg cultured meat product consisting of skeletal muscle cells with 30% dry matter content and 20% protein content	4.88-25.19 kg CO_2-eq/kg 94.09-532.78 MJ/kg 1.84-6.89 m2a crop-eq/kg 120-540 L/kg
Sinke and Odegard (2021)	Soy Hydrolysate, Glucose from Maize	1kg high-protein cultured meat product	2.5-13.6 kg CO_2-eq/kg 147-264 MJ/kg 1.7-1.8 m2a crop-eq/kg 42-56 L/kg
Mattick, Landis, Allenby and Genovese (2015)	Soy Hydrolysate, Glucose, Glutamine	1kg cultured meat product	3.15-22.28 kg CO_2-eq/kg 43.46-315.8 MJ/kg 2.92-8.47 m2a crop-eq/kg
Smetana, Mathys, Knoch and Heinz (2015)	Cyanobacteria Hydrolysate	1kg ready-to-eat product on consumers plate 3.75 MJ energy content of ready-to-eat product on consumers plate0.3 kg of digested proteins supplied to consumer	23.9-24.64 kg CO_2-eq/kg 290.7-373 MJ/kg 0.39-0.77 m2a crop-eq/kg
Tuomisto, Ellis and Haastrup (2014)	Cyanobacteria Hydrolysate, Wheat, Corn	1000kg ground cultured meat product with 30% dry matter content and 19% protein content	2.3-3.4 kg CO_2-eq/kg 38.7-60.9 MJ/kg 0.46 m2a crop-eq/kg 516.4 L/kg
Tuomisto and Teixeira de Mattos (2011)	Cyanobacteria Hydrolysate	1000kg ground cultured meat product with 30% dry matter content and 19% protein content	1.9-2.2 kg CO_2-eq/kg 26-33 MJ/kg 0.19-0.23 m2a crop-eq/kg 367-521 L/kg

Fig. 5. Cultured Meat Life Cycle Assessments (2010-2023)

4 Discussion

Systematically reviewing the CM literature landscape has highlighted significant knowledge gaps in our understanding of the environmental dimensions of this emerging biotechnology. Only eight LCA studies of CM were found in the existing literature. This deficit in environmental research also exists outside the confines of LCA research, with CM literature that focusses primarily on its environmental dimensions being rare. Considering the catastrophic environmental implications of present global meat production practices, the environmental potential of a transition towards CM is often a central feature of its public, media and industry discourse. However, environmental research constituted less than 10% of all CM literature published between 2010-2023. Within this <10%, the primary focus is predominantly on anthropocentric features of CM and the environment. For instance, emerging from the fields of psychology, philosophy, sociology and various other social sciences, discourse analyses and consumer acceptance studies comprise over half of all literature identified in this SLR as having any substantial level of environmental focus. Most of these studies feature the environment as a small subsection within their wider research, e.g., identifying potential environmental benefits as one of many factors influencing consumer acceptance. Focusing on human cognition and our socio-politico-economic systems, the environmental literature on CM primarily examines how we conceptualise it, what we think about its environmental impacts and where, or more specifically, if, it has a place in our diets within a climate changing world.

As is evident from the analysis of the literature, there is high variability within the results of the available CM LCA studies. This variability arises because of each study utilising a range of different system boundaries, LCI databases, LCIA methods and methodologies, and the inclusion of different system inputs and processes. The studies reviewed here adopted a wide variety of different approaches and therefore produced vastly different results. They also focused on different environmental impacts, with some studies choosing to omit water requirements i.e. [8] and others choosing to include data on aspects such as particulate matter formulation [11]. As the CM industry continues to expand and improve the systems, technologies and methods utilised in CM production, the accuracy of system-based information is increasing, and the anticipatory or hypothesised nature of CM's environmental impacts is becoming less uncertain. This is evident within the development of CM LCAs since the first published LCA study.

5 Conclusions, limitations and future research

This SLR adds to the growing body of environment-focused CM literature by providing a systematic and comprehensive assessment of the available LCA studies and their quantitative environmental impact assessment data.

There is a growing interest in the current literature about the potential of CM, specially in developed countries. The legal and environmental regulations from government would need to be considered if CM is to become mainstream. There is a potential that CM can help reduce GHG emissions substantially, therefore contributing to the amelioration of climate change negative impact.

LCA is grounded in systems thinking. However, one of its limitations is that it is not a method that can be utilised to provide generalised data on the environmental impacts of a certain product on a national or global scale, as the systems in which the product is made can differ significantly. For instance, the production of 1 kg of beef from a Concentrated Animal Feeding Operation (CAFO) situated in an arid region of the USA will have significantly different environmental impacts to those of the production of 1 kg of beef from pasture-raised cattle in the temperate UK climate. As is evident, a single LCA of beef production cannot be used to determine the environmental impacts of beef production on a global scale because the results will be context specific and may only be applicable only to the studied system and the product it creates.

Future research avenues include that LCAs should focus on ensuring a comprehensive system boundary that is inclusive of all relevant inputs during the production cycle. Adopting the approach outlined in [13] of including multiple FU's, this future LCA will avoid focusing on a singular mass-based FU at the expense of nutritional values. Further to this, multiple methods, e.g. [6] should be employed to identify the sensitivity of the results obtained during the initial study. Using the most recent industry data for the life cycle inventory inputs, adopting multiple life cycle impact assessment methods, assessing both mass and nutrition based functional units, and situating the hypothesised commercial-scale CM production system within specific geographical locations, will enable the elaboration of more comprehensive CM LCAs in future.

In summary, the following open issues have been identified in this paper, in the context of CM and LCA, there is a need for more research on:

- CM in the Environmental Sciences,
- Standardisation of LCAs methods,
- Agreement on the types of environmental impacts to consider,
- Inclusion of consumer perception data, and
- Legislation by governments to regulate scaling up of CM production.

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