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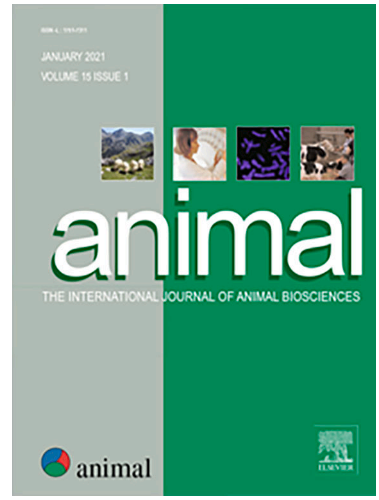

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Review: Will "cultured meat" transform our food system towards more sustainability?

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Highlights

- Cell-based food is still in developmental stage
- The number of scientific studies on "cultured meat" is moderate
- There are only few studies on safety, healthiness and environmental impacts
- The future of cell-based food is uncertain
- The cell-based food supply chain should demonstrate its sustainability

Abstract

Our agri-food system today should provide enough healthy food of good quality for the growing human population. However, it should also preserve natural resources and better protect livestock. In this context, some *FoodTech* companies are developing a disruptive approach: cell culture for *in vitro* food production of "meat" but this technology is still at the research and development stage. This article will highlight its development, the technologies used and the stakeholders involved (Part 1), its potential environmental impacts (Part 2) but also regulatory, social and ethical issues (Part 3). This article aims to shed light throughout the manuscript on two major controversies related to "cultured meat". The first controversy is related to its ethical aspects, which includes different points: its potential to reduce animal suffering and therefore to improve animal welfare, the future values of our society, a trend towards food artificialisation. The second controversy includes environmental, health and nutritional issues, in relation to characteristics and quality of "cultured meat" with an important question: should we call it meat? These two controversies act in interaction in association with related societal, legal and consequently political issues. Answers to the various questions depend on the different visions of the World by stakeholders, consumers and citizens. Some of them argue for a moderate or a strong reduction in livestock farming, or even the abolition of livestock farming perceived as an exploitation of farm animals. Others only want a reduction of the current much criticised intensive/industrial model. Compared with other potential sustainable solutions to be implemented such as reduction of food losses and waste, new food consumption habits with less proteins of animal sources, sustainable intensification, development of agroecological livestock production, or the development of the market for other meat substitutes (proteins from plants, mycoproteins, algae, insects, etc.), "cultured meat" has an uncertain future.

Key words: food systems, meat, cell-based food, FoodTech, sustainable diet

Implications

Cell-based food benefits from increasing media interest, growing investment and marketing approvals in Singapore and the USA. However, the number of scientific studies on "cultured meat" is moderate, and they often concern the technical processes or consumer acceptability surveys. There are only a few studies on safety, nutritional properties and environmental impact of this novel food, making it impossible to verify the claims made by companies in the sector with complete transparency. Ethical aspects are complex and concern not only animal welfare, but also human-animal relations, religious considerations, the future of livestock farming and the model of our agri-food system.

Introduction

Our agri-food system is confronted with many challenges. Indeed, the question of how today's agriculture will meet the future protein needs of the increasing human population (estimated at over 9 billion in 2050) has been a hotly debated issue for decades. The increase in food demand (around 70% on average) must take into account limited natural resources and climate change *(Sijpestijn et al., 2022)*. In this context, animal farming is highly criticised based on its disservices or negative externalities placed in an unfavourable light, whether it be, for example, the environmental consequences, the living conditions (welfare) and slaughter of the animals, the feed-food-fuel competition, or the risks to human health associated with overconsumption of red meat *(Pulina et al., 2022).* However, it should be pointed out at this stage that, whilst it is true that our dietary consumption of proteins of animal origin (including meat) is excessive in developed countries (about 2/3 of our protein consumption is of animal origin when it should be 50%, with an increase in obesity), the consumption of proteins is not enough in quantity and quality for some specific populations, especially in developing countries *(Chriki et al., 2020b; Sijpestijn et al., 2022).*
In some developed countries, the current trend with regard to meat is to consume "less but better" *(Liu et al., 2023)* following the example of wine over the last few decades (Laisney, 2016). It is above all intensive livestock farming that is criticized due to increasingly rejected practices (i.e. the high concentration of animals) (*Sijpestijn et al., 2022*). At the same time, the working conditions and incomes of farmers are not always up to par, in a context where, in beef farming for example, the Common Agricultural Policy support represents 175% of the earnings before tax.

In response to these challenges, sustainable ways of production should be developed. According to the FAO: "Sustainable diets are *those diets with low environmental impacts which contribute to food and nutrition security and to healthy life for present and future generations. Sustainable diets are (1) protective and respectful of biodiversity and ecosystems, (2) culturally acceptable, (3) accessible, (4) economically fair and affordable; (5) nutritionally adequate, safe and healthy; while (6) optimizing natural and human resources*" *(FAO, 2010; FAO and WHO, 2019).*
In line with this definition, various solutions have been proposed for livestock farming, such as the development of agroecological practices or sustainable intensification (i.e. increasing or maintaining agriculture on existing lands with a high productivity but with lower environmental impacts) *(Chriki et al., 2020b; Peyraud and MacLeod, 2020; Sijpestijn et al., 2022)*. At the same time, alternatives to meat (proteins from algae, plant-based products, mycoproteins, insects) are being developed *(Bourdrez and Chriki, 2022).* Some private companies are developing a new approach called "cellular agriculture" which is described as being able to produce meat and milk from animal cells rather than animals, in order to help solve some of the above issues *(Eibl et al., 2021; Poirier, 2022)*. Cellular agriculture includes various techniques to produce different products (gelatin, fats, dairy products, etc.). In this review, we will only focus on the production of "cultured meat", which is the most reported *FoodTech* innovation *(Chriki et al., 2020a),* and also the most controversial *(Chriki and Hocquette, 2020).* This can be explained by the fact that many of the potential benefits of "cultured meat" either for consumers

or for the environment are largely speculative *(Olenic and Thorrez, 2023)*, as cell-based foods are still in the research and therefore development stage.
After a brief reminder of the development and of the technological principles, we will address many issues around "cultured meat" by comparison with other solutions to provide food and proteins to human beings such as livestock farming. These issues will be discussed (i) from a technical and biological angle, (ii) from an environmental angle to solve current agricultural issues, and (ii) from a regulatory, ethical and social angle for marketing and to better understand consumer perceptions towards this novel product.

Current knowledge about "cultured meat"

Main stakeholders involved

The main stages in the history of cell-based food are shown in Table 1. Since 2015, many private companies have been founded (Figure 1) for instance in the USA (such as Memphis Meats, known as Upside Foods, now), in Israel (SuperMeat), in The Netherlands (Mosa Meat) and in other counties (Chriki et al., 2020a). These companies have stated that they will market "cultured meat" within the next 5 years *(Zhang et al., 2021).* The Good Food Institute (GFI), a non-profit organization established in 2016 and working internationally to promote innovation in meat substitutes, is also promoting cell-based food. As at the beginning of 2022, there were about 60 companies worldwide directly involved in "cultured meat" production out of a total of 112 companies, with the rest specializing in the production of other animal products (25 companies) or equipment or inputs for this activity (28 companies), according to the "Good Food Institute" (GFI).

Most of the companies are located in Europe (34, of which 14 are in the United Kingdom) and North America (33, of which 28 are in the United States), but also in Asia (22, of which 9 are in Singapore and 4 in China) and Israel (14) according to the GFI. Memphis Meats, now Upside Foods is still the leader followed by Mosa Meat in terms of investments *(Guan et al., 2021).* The vision of Upside Foods is based on science, future food and politics, with the ultimate objective to make "cultured meat" producible, edible and finally acceptable. In this strategy, the "cultured meat" producer is perceived as a major new stakeholder in our agri-food system like the farmer so far *(Stephens, 2021).*
Private investment has grown significantly and now stands at around US$3 billion with over 190 patents filed in 2021 *(Ng et al., 2021).* Public investment, although much smaller, is also beginning to develop, particularly in India, Singapore, Japan, Belgium and the European Community. If this sector expands, it will create new market opportunities, particularly for the production of everything needed upstream of the production of "cultured meat", such as bioreactors or culture media *(Choudhury et al., 2020).* Generally speaking, "cultured meat" is likely to be a highly integrated supply chain, considering as example the partnership between Impossible Foods and Burger King on the American market (review by *Mancini and Antonioli (2022)).*

"Cultured meat" in the academic scientific literature

Despite "cultured meat" technology being well developed by private companies, it is less present in academic research. Indeed, 327 scientific publications only were identified on this subject as of December 31, 2019 (*Chriki et al., 2020b*). The recent evolution of the scientific literature was analysed. Bibliometric data were retrieved from the Web of Science Core Collection. We used the same search query than previously *(Chriki et al., 2020b)* using the following terms “artificial meat” OR “meat in vitro” OR “in vitro meat” OR “cultured meat” OR “synthetic meat” OR “lab-grown meat” OR “lab meat” OR “cell-based meat” OR “clean meat” OR “fake meat” OR “slaughter-free meat” OR “cell-cultured meat” OR “craft meat” OR “cultivated meat” OR “victimless meat” OR “animal-free meat” OR “cruelty-free meat” OR “shmeat” OR “Frankenmeat” OR “test tube meat” OR “cellular meat.” The search was conducted within title, abstract, author keywords and keywordPlus fields using the field tags (TI, AB, AK, KP) on February 22, 2024.

The query was not restricted by publication years because we wanted to have chronological evolution. Seven corrections of articles and one retracted-article were removed from search results. By reading titles and abstracts, experts (i.e. authors of this manuscript) excluded 96 irrelevant articles mostly related to plant-based meat. Finally, 1027 scientific publications were analysed online, using Analyze Results Web of Science tool, on February 22, 2024. They were also downloaded in Tab delimited Format and imported in Sphinx Software the Lexica option, which allows statistical and text analysis, in particular for keywords analysis. These 1027 scientific publications include 186 reviews or book chapters.

Although the number of scientific publications on this topic has increased over the last three years (Figure 2), the total number of scientific articles remains modest and mainly on technological aspects. While the bibliometric search was carried out with more than 20 keywords, it appears that "cultured meat" is present in author keywords of 347 articles (Table 2, i.e. 34% of total items) and in titles of 248 articles (i.e. 24% in total but 27% from 2020 onwards). The top three journals publishing articles on this subject are Foods (41 articles), Frontiers in Sustainable Food Systems (33 articles) and Fleischwirtschaft (a technical international magazine for the meat industry with 27 articles). More than a third of scientific articles concerns the “Food Science and Technology” section (Table 2).

Authors originate mainly from the USA (217 articles), China (114 articles), the United Kingdom (94 articles), South Korea (66 articles), Germany (64 articles) and the Netherlands (62 articles). The three authors who publish the most are MJ Post from the Netherlands (21 articles), co-founder and chief scientific officer of Mosa Meat, SJ Ding from China (20 articles) and JF Hocquette (20 articles) from France who has a less technical point of view promoting an interdisciplinary approach (Table 3). More generally, the network of authors is very fragmented with about 15 groups of authors who do not publish together, which may reflect various approaches to this topic. To summarize, the scientific literature on “cultured meat” is limited but originates mainly from countries with an Anglo-Saxon or Germanic culture, and from China, which are the main supporters of this innovation *(Hocquette et al., 2023).*

Safe and healthy production with similar nutritional quality to animal products

In meat production, bacterial pathogens (for example *Salmonella, Listeria, Campylobacter* and *Escherichia coli*) can contaminate the food chain through various channels (e.g. transport of manure, contamination of meat via the digestive tract at slaughter or of water sources). Antibiotic-resistant pathogens are also a serious and important concern. Due to the absence of contact with the digestive organs at slaughter, ”cultured meat“ (where cells are grown in a suitable medium) is presented by its promoters to be safer than meat *(Shapiro, 2018)*. This highly controlled environment is supposed to limit epidemics. The consequences may be less costly vaccinations and less use of antibiotics (Chriki

and Hocquette, 2020; Post et al., 2020). However, antibiotics can be used as an input to the culture medium to prevent the growth of bacterial pathogens. Although the amount and nature of these antibiotics are still unknown, it is likely that the amount will be much less than that used in animal husbandry *(Ong et al., 2021; Mancini and Antonioli, 2022).*
The production of ”cultured meat“ is based on extensive muscle cell proliferation to produce a lot of “meat” from few cells. Regardless of the technical options, some genetic instability may occur due to the large number of cell multiplications (*Ong et al., 2021*). Therefore, for further quality assurance systems at the industrial level, the research should include search for regular monitoring of genetic stability *(Chen et al., 2022)* and, if applicable, for the potential impact of any genetic modification on the final quality of the product.
Because of the novelty of the cultured food production process and products, assurance of food safety and health value are among the main issues raised by nutritionists, food technologists, sanitary authorities and consumers. For this reason, several “cultured meat” companies have identified research priorities that concern:

- **(i)** standards for input residue levels,
- **(ii)** input levels including concentrations of growth promoters, antibiotics and any new molecules,
- **(iii)** recycling of media without concentrations of hazardous molecules,
- **(iv)** genetic modification and its potential consequences,
- **(v)** assessment of the composition and characteristics of the final product, etc. *(Ong et al., 2021).*

However, about safety of ”cultured meat“, little research has been transparently conducted and published so far (Ketelings et al., 2021). This is the reason why specific consultations on cell-based food products and food safety considerations are currently organised. For instance, FAO leaded in November 2022 such a consultation and an extensive list of more than 40 potential hazards have been identified in four different production steps (cell selection, production, harvesting, food processing and formulation). Many hazards are already well-known (such as microbiological contamination) as they exist in the conventionally produced food. However, some hazards are related to the materials used, inputs and ingredients added, and any type of equipment being specific to cell food production, such as any nutrient to nourish the cells; with some potential allergic reactions to them (FAO and WHO, 2023).
In general, the potential high variability and control by researchers of the composition of the culture medium (compared to the biological medium in live animals) can be an advantage for the control of safety as there will be less organic waste or possible contamination by pathogens from animals. In the same way, it may be possible to control the composition of the product by providing the relevant nutrients and in particular healthy fatty acids in the culture medium to ensure healthiness of the final product (*Marais-da-Silva et al., 2022b).* On the other hand, the range of possibilities in the composition of the culture medium allows for the addition of any molecule (hormone for example) whose biological effects are not well known. It is therefore necessary to study them. Some also argue that living animals have natural detoxification mechanisms (through the activity of their liver or kidneys, for example) that are not present in the production of "cultured meat" *(Lyer and Lyer, 2020).*
However, due to the immaturity of the technology, there are currently no prototypes of "cultured meat" used for an independent evaluation of its safety, sensory and nutritional qualities *(Fraeye et al., 2020).* On the basis of the available knowledge, and without the addition of molecules at the end of the manufacturing process, some scientists hypothesized that ”cultured meat“ may differ significantly from meat in its healthiness, e.g. due to a probably low iron content, the absence of myoglobin in cultured muscle tissue, etc. *(Fraeye et al., 2020).* In addition, the content in vitamin B12 of ”cultured meat“ should be studied to satisfy the dietary needs of consumers. Furthermore, the chemical components of the culture medium or of biomaterials used to produce “cultured meat” could inhibit the health benefits of some specific micronutrients such as iron *(Chriki et al., 2022).*
Another major gap of knowledge lies in the aging and conservation of "cultured meat" over the more or less long term (*Munteanu et al., 2021)*. According to the scientific literature published so far, these

aspects have never been studied *(Munteanu et al., 2021),* despite their importance for the safety, as well as the sensory and nutritional qualities of the meat product.

Implementation of low-cost and efficient, mass production techniques

The technique of growing muscle cells in Petri dishes on a laboratory scale is widely used in both academic and private laboratories. Therefore, M. Post in 2013 made his first "artificial hamburger" by scraping off the muscle cells lining the bottom of the Petri dishes. Then, a large number of cell layers from this process were stacked.

To produce "meat", with regard to the process itself, it is necessary to use scaffolds that allow the cells to attach and then to assemble into a tissue that looks like conventional meat. The composition of this biomaterial should be of a reasonable cost but also compatible with human food to allow large-scale production *(Post and Hocquette, 2017; Chen et al., 2022).*

The design of new types of high-capacity bioreactors is therefore necessary to produce large quantities of muscle fibers. For example, some research teams are designing incubators with suspended microbeads for cell attachment *(Bodiou et al., 2020)*. Other three-dimensional (3D) culture techniques are of interest, with branched supports to attach cell aggregates, incubators with variable volume to be adapted to stage or size of cultures (*Moritz et al., 2015)* or large-scale air-lift reactors *(Li et al., 2020).* The aim is to optimise dispersion of cells and occupancy of the incubator volume so that cells will not be limited in their multiplication.

The cost for synthesizing hormones and growth factors to include in the culture medium is the major cost *(Chen et al., 2022).* Many companies have pledged to move away from fetal bovine serum (FBS), which is an expensive, biologically variable ingredient that raises technological and ethical problems *(Chen et al., 2022)* and some research has already been conducted in this direction *(Lee et al., 2022).* Different options have been explored 1) microbial fermentations to synthesize recombinant growth proteins, or 2) non-animal extracts, for example from plant proteins or from plant hydrolysates. Recently, key cellular signals have been identified using an omic approach. These signals are supposed to allow myocytes to grow without FBS *(Domigan et al., 2022; Messmer et al., 2022).* Recycling of culture media can further reduce costs and the company "Future Meat" is working in that direction.

In all cases, private companies have identified the key parameters to work on from a technical and economic point of view, namely, the distribution of gases (O_2, CO_2), the circulation or renewal of the culture medium, the absence of contamination by micro-organisms (bacteria and fungi), and the determination and control of the optimal culture temperature. Technically, private companies aim to reproduce hormonal, biochemical and mechanical stimuli involved in cell multiplication and differentiation *(Post and Hocquette, 2017*). Economically, private companies aim is to cut down production costs. This research can benefit from new scientific approaches such as artificial intelligence, machine learning and computer modeling, potentially useful for monitoring large-scale production parameters.

Production of meat products in all their biological and organoleptic complexity

While the first "cultured meat" produced in 2013 resembled a burger, the most technically challenging strategy is to reproduce the complexity of the muscle tissue so that the final product can resemble a rib-eye steak, chicken leg or pork chop. This is theoretically possible because stem cells can be converted into different cell types: myoblasts to synthesize muscle fibers, pre-adipocytes to produce intramuscular fat tissues, fibroblasts which synthetize collagen, or other cells to get nerves or blood vessels. These different cell types (myoblasts, adipocytes, fibroblasts, etc) should therefore be cultured together to ultimately produce a piece of tissue that looks like muscle as done by the company Aleph Farms (*review by Chriki et al.* (2020c)*).* However, co-culture of multiple cell types is technically difficult, because each cell type grows and differentiates under specific conditions that differ from one cell type to another. Therefore, when multiple cell types are co-cultured with the same medium, all conditions should be suboptimal for the different cell types (unless FBS is used, with the limitations mentioned above). However, we know that supplementing culture media with different molecules, such as proline or ascorbic acid, can direct cells towards an accumulated deposit of extracellular matrix, thus modifying the mechanical properties of muscle tissue *(Thorrez et al., 2018; Olenic and Thorrez, 2023).* Consequently, with the current state of the art, the muscle produced appears rather thin. Only millimetre-thick bovine tissue *(Furuhashi et al., 2021)* or "cultured meatballs" *(Liu et al., 2022)* have been produced so far. The development of co-cultures with different cell types for growing connective tissue as a support for organized muscle cells with blood vessels, fat cells and nerves, is a complex technical and economic challenges *(Chen et al., 2022).*

Environmental performance of these technologies

Greenhouse gas production

Greenhouse gas (GHG) emissions into the atmosphere are now considered to be the main cause of global warming. "Cultured meat" is presented as more virtuous than livestock farming in terms of GHG emissions. In reality, only a few scientific studies on this topic have been found, despite a few reports in the "grey literature" (which are not considered as lacking peer review process). Moreover, the lack of real industrial data related to "cultured meat" led to a low level of robustness of these studies which are based on too many assumptions. The low amount of industrial data related to the proliferation and differentiation phases in the bioreactors is a problem. Furthermore, of all the important points to be considered (cell harvesting, growth factor production, biological support material production, bioreactor production, bioreactor cleaning, culture medium recycling, biomaterial recycling, water treatment), only one or two were included in the cited studies (mainly the direct production of "cultured meat" in bioreactors). Therefore, the studies carried out so far are deemed as unreliable or insufficient *(Rodríguez Escobar et al., 2021)*.
Another study *(Smetana et al., 2015)* compared several protein sources. Using one kg of food as a reference unit, the environmental impact is highest for "cultured meat" (after chicken and mushroom proteins) due to the immaturity of the technical process and high energy demand for it (including culture media production and cell multiplication/differentiation). Products with the least impact are insect production and meat substitutes from soybeans due to efficient technologies and recycling of by-products. If other functional units such as calories or protein are used, "cultured meat" remains the most impactful food *(Smetana et al., 2015)*.
In parallel, another study by *Mattick et al. (2015)* concluded that "cultured meat" production may have lower GHG emissions than beef production, but would be higher than chicken and pork production. The higher environmental impact of "cultured meat" in the *Mattick et al. (2015)* study compared to the original work of *Tuomisto and de Mattos (2011)* could be explained by the consideration of impacts for the production of culture media and the cleaning of equipment which must be regular and frequent, and also, although to a lesser extent, by different methodologies.
More recently, another study by *Lynch and Pierrehumbert (2019)* examined the different characteristics of GHGs: CO_2 has a lifetime of more than 100 years in the atmosphere compared to only about 12 years for methane (CH_4). However, CH_4 is known to have a warming effect 28 times more powerful than CO_2. After analysing several scenarios, the authors concluded that "cultured meat" has no obvious long-term benefits in terms of environmental impacts because it will induce CO_2 production, due to the energy used to have incubators at physiological temperature and to prepare

equipment and culture media.
These studies all show that production of the culture medium (including the production of each ingredient of it) and the energy consumption for cell culture in bioreactors are the major sources of GHG emissions *(Tuomisto et al., 2022)*. Consequently, optimisation of culture medium production may have a major impact on the overall emissions *(Smetana et al., 2015)*. In addition, the different methods used to assess global warming also have a great impact on the results *(Lynch and Pierrehumbert, 2019).*
A publication on this issue *(Sinke et al., 2023)* funded by a private organization has compiled primary data from 15 companies active in ″cultured meat“ sector who commissioned the study. The carbon impact varies by a factor of 5, depending on the type of energy used between the least and most virtuous processes (i.e. with or without renewable energy sources), while energy consumption can vary by a factor of 1.8 between the extreme scenarios. However, the results are within the orders of magnitude of those of *Mattick et al. (2015)* and therefore superior to those of *Tuomisto and de Mattos (2011)*, thus invalidating this early work published over 10 years ago. The same report stresses the uncertainty of its estimates and the need to compare results for the same energy source used for both meat and "cultured meat" production. While concluding that the production of the latter may be more virtuous than the production of meat, particularly beef, it will always have more environmental impacts than the production of plant proteins. However, livestock farming including beef production could also in the future improve its GHG balance, whether in terms of reducing emissions (through the choice of diet or the selection of farm animals, for example) or better storage, particularly in soils of permanent pastures.
In order to fill the gaps in the literature, a complete production system was modelled and analysed with methods inspired by Life Cycle Assessments (LCA). Using this approach, there are not only technical difficulties in designing the production system in detail, but also difficulties in collecting or estimating the environmental impacts of each stage of the process. This is particularly true for the production of the culture medium as the environmental impacts related to the manufacture of each of its components (carbohydrates, lipids, amino acids, hormones, vitamins, inorganic salts, buffer, etc.) are not known. All the authors previously mentioned agree that the uncertainty regarding the manufacture of the culture medium is a major cause of the great variability in the estimation of GHG emissions to produce ″cultured meat″ *(Rodríguez Escobar et al., 2021)*. In addition, some authors argue that existing life cycle analyzes for producing "meat" by cell culture are insufficient to assess the real environmental impact of this novel technology. The main problem with existing studies is that the models used do not fully reflect the current or emerging processes that will be used to manufacture these products. Therefore, a very recent study has suggested a much higher environmental impact for "cultured meat" than for the production of beef with the use of highly purified culture media *(Risner et al., 2023)*.

Water consumption and discharge of waste into the environment

It is common to hear in the press media that 15 000 L of fresh water would be needed to produce 1 kg of beef, and this reference figure can be wrongly compared to the water production for 1 kg of ″cultured meat″. Indeed, 95% of this 15 000 L water correspond to water evapotranspired (and therefore strongly correlated to rainfall) by the surfaces intended for livestock farming such as meadows and pastures in particular. This water consumption is called "virtual" water, as it would also be accounted for without the farm animals *(Doreau and Corson, 2017)*. A more accurate estimate of water actually consumed to produce 1 kg of beef is based only on the water actually consumed by buildings for livestock, crop irrigation and the water consumed by the animals. This value generally oscillates between 550 and 700 L/kg for beef (vs. 313 L/kg for chicken and 459 L/kg for pork) *(Doreau and Corson, 2017)* previously announced. As ″cultured meat“ is a completely novel product, the quantities of water needed for its production are only estimates. The figures reported are 367-521 L/kg based on the work of *Tuomisto and de Mattos (2011*), which is of a similar level to beef production. The same researchers acknowledged that the use of the 15 000 L/kg figure leads to a highly

exaggerated assessment of the gap *(Tuomisto et al., 2014)*.
In addition, the question of water quality arises, as the release into the environment of organic or synthetic molecules to synthetize the culture media or after having used it cannot be excluded even after wastewater treatment *(Hocquette, 2015)*. Generally speaking, the efficiency of nutrient conversion for the manufacture of "cultured meat" is not known but the costs of managing residual nutrients in the culture medium, linked to wastewater treatment and land application, may be higher than for meat production by animal farming *(Myers et al., 2023)*.
The environmental impact of wastewater from agriculture should be an issue and the two issues need to be compared *(Munteanu et al., 2021)*. Indeed, we should also consider wastewater from conventional meat production, including risks stemming from antibiotic resistance development, veterinary medication and organic load which are conveyed to the environment through wastewater as well as farm and slaughterhouse residues.

Land use

At the global level, the unfrozen land surface (13.2 billion hectares) can be divided in (i) agricultural land (38%, i.e. 5 billion hectares) and (ii) non-agricultural land (62%, including cities, deserts and forests). The agricultural land itself is divided into (i) arable land (9%) used for crop production (and therefore not for livestock production), (ii) arable land used for the production of animal feed (4%) and (iii) non-arable agricultural land (25%) used for livestock production thanks to pastures (grasslands, mountain areas, steppes and rangelands). Further calculation shows that more than half of land used for livestock production (1.3 billion over 2.5 billion hectares) corresponds to non-arable land, which can only be used by livestock, and in particular herbivores, which have the capacity to convert the grass and fodder into noble, protein-rich foodstuffs (dairy and meat products) directly used by humans *(Mottet et al., 2017)*.
Clearly, therefore, the production of "cultured meat" will require less land when expressed in hectares *(Munteanu et al., 2021; Treich, 2021)*. However, it would be necessary to quantify the land occupied by the upstream industry for the production of the equipment (incubator, etc.) and the different components of the culture medium (review by *(Mancini and Antonioli, 2022)*). In addition, it is important to note that the removal of livestock from non-arable grasslands would result in a decrease in overall food production for humans. This is because there is only competition between food and feed on 4% of the total unfrozen land. Moreover, livestock farming provides numerous benefits, such as environmental services (e.g. plant and animal biodiversity in grasslands but also landscape maintenance) or social services (e.g. maintaining farmers and therefore a rural population in areas that have been abandoned by our now mostly urban citizens (review by *Chriki et al., 2020c)*). Therefore, it would be interesting to evaluate the cost of the services provided by livestock farming (particularly in terms of environmental impacts) by comparing two options: 1) services and impacts with less livestock if cellular agriculture develops and 2) services delivered by agroecosystems when obtained with a strong contribution from livestock systems as it is now.
Thus, a decrease in livestock farming as a result of the development of the cell-based food supply chain could have many unpredictable consequences on landscapes and the maintenance of the human population in the countryside. This is why some academic researchers favor the path of agroecology in order to maintain these positive externalities of livestock farming *(Dumont et al., 2020)*.

Combined approaches

The latest publication on this topic *(Tuomisto et al., 2022)* was based on utilisation of real data about nutrient requirements of laboratory-scale muscle lines, instead of modelling approaches. Nine different environmental indicators were used including, as in previous studies, energy demand, global warming, land use and water consumption *(Tuomisto et al., 2011)* but also fossil resource scarcity, freshwater eutrophication, ozone formation, particulate matter and terrestrial acidification *(Tuomisto* *et al., 2022)*. The system which has been studied includes the main steps of the process: extraction of raw materials as muscle cells, production of inputs (scaffold, nutrients, water sourcing, energy, oxygen, medium components), requirements for cell proliferation and differentiation in bioreactors, temperature control during the process and cleaning of the bioreactor. However, production of facilities (buildings, bioreactors, equipment), product formulation units and packaging of the product were not considered. Results indicated that the contribution of the production of the “cultured meat” ingredients to the environmental impacts varies between 48 to 89%. The production of amino acids contributes the most to the environmental impacts of the culture medium, followed by the production of glucose, and vitamins and minerals. Three scenarios were studied: a baseline one, a scenario with a 128% cell biomass increase during differentiation and a scenario where renewable energy was used instead of electricity. The highest environmental impacts were observed for the first scenario, but with a huge variability. The highest reduction in all the environmental indicators were achieved through changing the cell types and with a 128% cell biomass increase during differentiation. These observations are mainly due to a decrease in requirements to produce the culture medium. Generally speaking, results were thus most sensitive to cell metabolism and cell mass increase during differentiation. Therefore, results also depend on cell line. Reductions were also achieved through use of renewable energy sources such as wind or solar energy when they replace electricity. When compared to meat produced by farm animals, environmental impacts of meat production though cellular agriculture were always higher than those of poultry meat production *(Tuomisto et al., 2022)*.

Regulatory, social and ethical issues

Legislation and issues prior to authorization and commercial launch

According to European regulations, meat for commercial purposes is defined as "the skeletal muscle of mammalian and avian species recognised as fit for human consumption". This is why "cultured meat" falls into the category of "novel foods" under European legislation. Furthermore, according to the definition of the American Meat Science Association *(Boler and Woerner, 2017*), meat is also defined as "the edible tissue of an animal consumed as food … To be considered meat, "cultured meat" meat must originate from an animal cell, be inspected and considered safe for consumption, and be comparable in composition and sensory characteristics to meat derived naturally from animals". Currently, only Singapore, and more recently the USA and Israel, high-income and high-tech countries, have approved the commercialization of “cultured meat“ for human consumption, although intense negotiations are taking place in major regions of the world. In addition, the Czech start-up Bene Meat Technologies is the first to win European Union registration for laboratory-grown meat for use in pet food.
In view of these regulatory issues, the development of the "cultured meat" supply chain would require increasing state control of the technology (review by *(Mancini and Antonioli, 2022))* due to new technical questions, related to fears expressed by consumers, safety or “cultured meat” composition (unknown until now).In case where the approach to obtaining muscle cells is based on the use of cell lines, i.e. cells made immortal by genetic techniques, the resulting product falls under GMO legislation, which raises further questions.

Social changes

The production costs of "cultured meat" are decreasing. Indeed, while the cost of the first burger produced in 2013 was estimated at more than €2 million per kg, a "cultured meat" patty in 2016 cost only €36,000 per kg, and chicken "cultured meat" in 2017 cost only €17 000 per kilogram. The steak developed by the company Aleph Farms was in 2018 around 45 € for a thin slice (about 5 mm thick). However, high price is still an issue although parity with conventional meat may be achieved in the coming years (Chriki et al., 2020c; Morais-da-Silva et al., 2022a). As indicated by the Good Food Institute, the challenges are serious: current production costs are 100 to 10 000 times higher than for meat according to CE Delft analysts. Despite this, the Good Food Institute anticipates that the cost of producing one kilogram of "cultured meat" will fall to a target of $5.66 by 2030. However, other authors have highlighted announcements not followed by facts, such as date of arrival on the market or reduction in price *(Fournier and Lepiller, 2019 ; Wood et al., 2023).*

For several decades now, we have been talking about "disruption" or the destabilization of economic markets, with Uber in the taxi industry and AirBnB in the hotel market as emblematic examples. Today, even if the market mechanisms and rules are different between these sectors, the meat market, stable until now, is about to suffer the same fate due to a strategy of "cognitive encirclement" according to some authors. The promoters of alternative proteins including "cultured meat", who have detected a new potential market, have developed an effective communication strategy, with an elaborate rhetoric *(Fournier and Lepiller, 2019)*. On the other side, the rhetoric for conventional meat is also criticized *(Hannan, 2020).* The communication from promoters of alternative proteins is based on two current trends (concerns for the environment and the animal cause) that correspond to strong normative injunctions in the agri-food sector *(Fournier and Lepiller, 2019)*. The challenge is to convince consumers to accept "cultured meat" and any other alternative proteins. Some actors but not all aim to reach this goal by discouraging consumers from consuming "classic" meat for ethical and environmental reasons *(Morais-da-Silva et al., 2022a),* based on the principle that the future lies in avant-garde concepts or innovations *(Fournier and Lepiller, 2019)* to emancipate animals from livestock farming. Consequently, some key stakeholders, but not all, are funding both various animal rights associations and organizations that help "cultured meat" start-ups or other organisations such as The Good Food Institute. In addition, these stakeholders are very active with the goal to obtain marketing authorizations (an essential step), with different strategies depending on the political context of the states, which differs for example between the USA and Europe. Although the economic challenges are huge for the conventional meat market, the market for "cultured meat" is still uncertain: it could be a luxury product that is still an expensive one or a cheap product for the mass market within nuggets or burgers. Furthermore, insects and "cultured meat" are less preferred by consumers compared to other alternatives *(Hamlin et al., 2022*).

Another question concerns the governance of the potential "cell-based food" supply chain, given the high-level technical expertise and also the huge investments required for this production. The development of "cultured meat" production is thus likely to widen the disparity between the countries of the North that have the expertise, the means and the money and the countries of the South that have immense food needs. This question may become crucial if the development of "cultured meat" is mainly explained by powerful economic issues as well as by economic and political alliances and less by ethical issues as recently claimed by some authors *(Porcher, 2023).*

Nomenclature and misuse of agri-food vocabulary

Some actors see the development of so-called "cellular agriculture" as a revolutionary breakthrough in human history, as important as the domestication of animals. This means that a complete transformation of our agri-food system is underway, prompting the stakeholders of this evolution to use the vocabulary of agriculture and food. Indeed, as with any other field, agrifood vocabulary is dynamic and will transform itself as the real-life practices and concepts change because language is not static. However, the wording "cellular agriculture" is criticized by some linguists. Indeed, agriculture means "cultivation of the fields" because it comes from the Latin *agricultura*, composed of *ager*, "field", and *cultura*, "culture". It does not make sense to express the two concepts of cell culture and field culture in the same word. Furthermore, some authors consider “cellular agriculture” as the epitome of industrial animal farming *(Poirier, 2022)*. On the other side, its most emblematic technology (“cultured meat”) is presented as an alternative to intensive farming livestock systems.

Moreover, the field of "cultured meat" is not yet stabilized since there are at least 24 names used in the specialized or general press for this product, ranging from "*in vitro* meat" to "vegetarian or even vegan meat", including "clean meat" or "violence-free meat" *(FAO and WHO, 2023)*. The name used reflects the perception of this product by the authors of the articles (Fournier and Lepiller, 2019; Chriki et al., 2020a). However, in the majority of cases, the frequent use of the word 'meat' has led to an ambiguity favourable to the proponents of cell-based food, who take advantage of the positive values of meat as perceived by consumers (health, strength, vitality,etc.) *(Chriki et al., 2022).*
For farmers, “cultured meat” is not meat because meat also represents all the life, the love of the animal, the work of the farmer and the local land or local territories. This is why some agricultural unions advocate the banning of the word 'meat' to describe this new product *(Fournier and Lepiller, 2019).* Farmers and other livestock stakeholders are keen to point out that livestock farming also produces positive externalities: the maintenance of landscapes and biodiversity, the production of natural fertilizers for example. For the butcher but also the biologist, there is as much difference between grape juice and wine, as between muscle and meat, as wine results from the conversion of grapes thanks to a biological transformation (vinification). Similarly, aging of muscle is a complex natural biological phenomenon which is necessary to produce meat (review by *(Chriki et al., 2020a)).*

Consumer perception

The main drivers of food (and meat in particular) purchase in all countries are an affordable price and a high sensory quality. In addition, meat consumption also depends on consumer demographics (gender, age, country of origin, eating habits and other social parameters) *(Liu et al., 2023).* The same factors are also drivers of potential acceptance of “cultured meat” as described below.
Various surveys have been conducted in various countries *(Bryant and Barnett, 2020)* and difficulties in consumer acceptance of “cultured meat” has been shown as a major social challenge *(Morais-da-Silva et al., 2022a).* More recently, the same survey was conducted online in fourth different regions in the world: Africa *(Kombolo Ngah et al., 2023)*, France *(Hocquette et al., 2022),* China *(Liu et al., 2021)* and Brazil *(Chriki et al., 2021)*, to study consumer opinions on “cultured meat” involving at least 4 500 consumers of different profiles in each country or region. According to the vast majority of respondents (over 89% in Africa, 91% in France, 95% in Brazil and 96% in China), the selling price of this product should be lower (or even zero for those who do not want to buy it) or equal to that of meat. Depending on the country, 15% (in China) to 54% (in France) of respondents considered "cultured meat" to be an "absurd and/or disgusting" idea, compared to 19% (in France) to 47% (in Brazil) who considered it to be a "promising and/or feasible" idea. These proportions also vary according to sociological groups. While the majority of respondents said they would be willing to taste "cultured meat", this is mainly out of curiosity. Therefore, it does not mean that they would consume it regularly. Generally, respondents’ countries of origin, age, gender and education level regulate willingness to try, to eat or to pay. However, we observed many interactions between these factors. For instance, African respondents from the richest and most educated countries tended to be more willing to try “cultured meat” (Kombolo Ngah et al., 2023).
Contrary to the situation in China, women in France and Brazil seemed to be more in favor of this biotechnology than men, due to an increased sensitivity to the ethical or environmental issues associated to livestock farming. Men over the age of 51, especially those in the meat sector, were the most reluctant. Although 40-50% of French respondents considered that livestock farming is facing

ethical and environmental problems, only 18-26% of them thought that "cultured meat" could solve these problems. Furthermore, a majority of French respondents considered that "cultured meat" would be neither healthy, nor tasty, nor natural *(Hocquette et al., 2022).* Generally speaking, potential consumers of "cultured meat" are indeed more sensitive to arguments (positive or negative) relating to their good health and to the pleasure of eating meat of high sensory quality than to environmental or animal welfare considerations *(Gomez-Luciano et al., 2019).*
The study conducted in Brazil showed that slightly more than half of the respondents did not agree with the name "meat" for this new product *(Chriki et al., 2021).* Furthermore, unlike about half of the meat consumers, vegetarians and vegans perceived this new product as meat and therefore do not want to consume it *(Gousset et al., 2022).*
Other work has suggested that in some countries such as China or Israel, "cultured meat" is considered as a solution to food security problems or to use much less land, water and inputs. In India, where cattle is a sacred species, "cultured meat" could be adopted to protect the animals. In Indonesia, Qatar and Malaysia, countries with a Muslim majority, "cultured meat" has been recognized as Halal and therefore suitable for consumption, although this is a matter of debate in the Muslim community (review by *Chriki et al.* (2020c)). In all these cases, governments can encourage investments as citizens in China (59%), followed by India (56%), are more likely to buy "cultured meat" than those in the USA (30%) *(Bryant et al., 2019)*
Another survey was carried out in Australia to compare the perception of meat and of meat substitutes either plant-based products or "cultured meat" according to six attributes: safety, price, health, food enjoyment, animal welfare and potential environmental benefits. For all attributes, perceptions of plant-based meat alternatives were more positive than those associated with "cultured meat". For animal welfare and environmental benefits, plant-based products were perceived more positively than all other products *(de Oliveira Padilha et al., 2022)*. As in previous surveys, the factors which may explain variability in willingness to consume cultured meat products include 1) positive perceptions regarding food experience (enjoyment), safety issues, concern about animal welfare and health; 2) product knowledge; 3) younger age and advanced or "tertiary" education. Although "cultured meat" is presented as being better for the environment, the consumers interviewed did not seem to be convinced of this *(de Oliveira Padilha et al., 2022).*
In addition, "cultured meat" sometimes suffers from the bad image of genetically modified organisms (GMOs), either because consumers may wrongly assume that "cultured meat" is a GMO (which is not true, except in the case of the use of cell lines), or because it is perceived as an industrial food product like GMOs. Some of the potential benefits of "cultured meat", such as the ability to control the composition of the product, may also be misunderstood because they highlight the possibility of manipulating the product by unacceptable means. The fact that (almost) anything is possible can also be worrying, for example, the idea of consuming 'meat' produced from human cells or even from our own muscle cells. "Cultured meat" is also perceived as an unnatural product (Liu et al., 2021; Chriki et al., 2021; Hocquette et al., 2022). Moreover, it is well known that topics perceived as highly innovative are prized by the media, which often present them in a positive light. As in other fields, the communication war has therefore become a major issue, especially for start-ups looking to produce "cultured meat" and whose ambition is to "educate consumers".

Ethics: human-animal relationship, future of livestock farming, religious brakes

"Cultured meat" may reduce the number of animals slaughtered. According to some authors, this will induce a major reduction in animal suffering. This may be a strong moral justification to adopt cell-based food *(Heidemann et al., 2020; Treich, 2021; Morais-da-Silva et al., 2022a).* However, it still requires a few animals from which these samples would be routinely taken *(Chriki et al., 2022).* Nevertheless, the biopsy is considered a minor stress *(Munteanu et al., 2021).* However, repetition of the procedure has never been studied in terms of long-term stress to the animals. Furthermore, some authors have argued that animal welfare would be degraded in farms that persist due to increased and tougher competition between them and with meat alternatives for economic profitability (review by *Mancini and Antonioli (2022)).*

Other ethical questions concern the composition of the culture medium, which must contain hormones and growth factors to provide them to cultured cells. So far, these are provided by FBS which is from foetus of pregnant cows. As this process is not only unethical but also expensive, all start-ups are successfully working on developing culture media without animal serum *(Messmer et al., 2022).* However, the only "cultured meat" currently on the market (in Singapore) is produced with FBS. This was also the case for the first "artificial burger" produced in 2013 by M. Post.

In addition, "cultured meat" is part of a more global problem that questions the relationships humans have with domestic animals, with their food and with farmers. For instance, since farmed animals are so dependent on humans, we will need to prepare them before they are returned to the wild if transition to "cultured meat" will be quick *(Chriki et al., 2022).* In case of a gradual transition, reproduction of farmed animals should be limited and excess animals should be consumed. On the other hand, some argue that livestock farming (and thus meat production) is a win-win strategy between the domestic animal and humans, with the latter protecting the former from predators and keeping it healthy in exchange for eggs, milk, meat or other products *(Porcher, 2017).* This point of view is not acceptable to animal advocates.

"Cultured meat" is sometimes perceived as a challenge, particularly by farmers and meat professionals *(Morais-da-Silva et al., 2022b),* whose sector has already been weakened. This concern goes even further, with fears about the future of our countryside, particularly in terms of maintaining the landscape and the rural activity. It could be argued that this is more a question of a change in jobs than a straightforward elimination, and that the economic development of a new sector would generate wealth.

Towards a reshaping of our agri-food system?

Some companies in the sector consider that "cultured meat" will initially be a niche market for high-quality products with expected benefits for the protection of animals and the planet, to which the richest consumers (who also have the highest willingness to pay) are the most sensitive. However, in this scenario, the small deployment of "cultured meat" would never be such as to significantly reduce the environmental impacts of farm animals.

In a second phase, if the dynamism of investors continues, if the cost of production decreases, and if government support is present, the development of the "cultured meat" sector would extend to the mass market, which may result in a decrease in livestock, the number of farm and a desertification of the countryside *(Chriki et al., 2022).* On the contrary, employment would increase in the cities for the production of "cultured meat". This would change the balance within countries, or between countries, with highly developed urban regions in which the production facilities would develop, damaging the livelihoods and income levels of rural populations in territories, which depend on livestock. The concentration of investments into a few hands is also likely to lead to an imbalance of economic power *(Mancini and Antonioli, 2022).* The development of "cultured meat" is likely to cause a shift from conventional meat production to a high-end market. Consequently, meat would become an expensive luxury product (review by *Mancini and Antonioli, 2022).*

However, some actors consider "cultured meat" as a step towards the end of animal exploitation for a more sustainable and healthier lifestyle *(Munteanu et al., 2021).* This argument is not acceptable to the supporters of gastronomy and the culinary tradition of meat. More generally, the development of "cultured meat" could induce a standardization of the meat product (like fast food) and to a loss of the cultural diversity associated with food. Furthermore, the pleasure of eating meat could also be greatly reduced or at least modified, which would go against the satisfaction of human well-being according to most gastronomes.

Other authors argue that conventional meat and "cultured meat" may coexist with other meat alternatives. In this case, "cultured meat" could be incorporated into hybrid products with other alternatives that can provide sufficient nutrients to consumers. Similarly, meat alternatives may be not in competition with livestock farming or with other sustainable solutions, such as the reduction of food waste and losses, because they are rather complementary.

In this discussion, we should consider all benefits and weaknesses of livestock farming systems (and sustainability of these systems) which are nowadays listed according to five dimensions based on the methodology by *Ryschawy et al. (2019*): 1) production of food products which are safe and healthy for human consumption; 2) interactions with the environment (land and water use, greenhouse gas emissions, biodiversity, soil fertility, etc.); 3) opportunities of jobs (direct and indirect) with good conditions of work; 4) societal issues such as animal health and welfare, food consumption habits, cultural gastronomy, etc. and finally, 5) inputs necessary to produce food.

As indicated above, compared to meat from farm animals, "cultured meat" has not yet proven yet to be so healthy or so nutritious due to lack of data. Research in nutrition with digestibility approaches has to be conducted to study absorption of nutrients from "cultured meat" by the digestive tract of human beings. Regarding interactions with the environment, livestock farming systems have weaknesses but also benefits not considered yet. In addition, the social network is likely to be changed as a consequence of a lower number of traditional farms and of a lower number of farm animals. The development of the "cultured meat" industry is also likely to change our food system, its organization (from producers to consumers), our food habits with less focus on culinary traditions. The business sustainability is also important, this means designing new business models and management rules to address the sustainable development goals *(Nobre, 2022).* However, it is very difficult to anticipate which food protein types will be the highest in demand in the long-term future, depending on their respective sensory, nutritional, ethical and environmental attributes *(Biscarra-Bellio et al., 2023)* considering that some authors argue that any alternative protein will not disrupt the meat market *(Siegrist and Hartmann, 2023).*

Thus, "cultured meat" is at a crossroads with several possible scenarios: (i) The first scenario would be the failure of the development of "cultured meat" due to unfulfilled promises by start-ups, lack of support from public authorities and consumers who remain unconvinced. In this scenario, one may assume that the market for other meat substitutes may increase or decrease. This scenario is likely to corresponds to the "technocratic stagnation" scenario of *Moritz et al. (2023).* It is driven by perceived threats and unwillingness to accept "cultured meat" by stakeholders and/or consumers. (ii) The second scenario is the opposite, based on ever greater investments, spectacular technical progress and support from governments and consumers, which would lead to a sharp reduction of intensive livestock farming replaced by "cultured meat". This implies a sharp reduction in the cost of "cultured meat". Thus, pragmatic consumers would adopt the product for economic reasons. In this scenario, only positively perceived extensive livestock farming would remain to produce a meat considered as a luxury product. This scenario is likely to correspond to the "rapid advancement" of *Moritz et al (2023).* It will be driven by technological breakthroughs and high acceptance and development of "cultured meat", leading to radical and permanent changes in our food system. (iii) The third scenario is logically situated between the first two: livestock farming would remain largely present for consumers attached to meat and to the culinary history of their countries, while meat substitutes, including "cultured meat", would develop for environmental and ethical reasons. Hybrid substitutes mixing plant proteins and "cultured meat" are likely to develop first because of the still high cost of muscle cultures. However, the limited market penetration of "cultured meat" alone would be a major obstacle to solving the current ethical and environmental problems. This scenario may correspond to the "promising circumstances" scenario of Moritz et al (2023) characterised by a positive societal context for "cultured meat" development and an incremental adoption of this novel product by stakeholders and consumers as an additional food product on the market.

At present, the current scenario looks like scenario 1 in that "cultured meat" is not present on the market. It is allowed for commercialisation in Singapore and more recently in the USA and in Israel.

Scenario 2 is clearly the least likely because of the highly significant technical, regulatory and social obstacles to be overcome. The question is whether it is possible to move to scenario 3, a question that remains unanswered today because of the many technical, regulatory, political and social uncertainties and the lack of transparency from "cultured meat" producers.

Conclusion and outlook

“Cultured meat” raises many debates and controversies. The technical aspects, although surrounded by great uncertainty, are the easiest to deal with, because they are based on factual observations. In order to become a credible alternative, "cultured meat" must offer real and proven added value compared to meat in terms of safety, nutritional benefits and/or reduced environmental footprint. This is not (yet) the case.

It is clear that the “cultured meat” industry lacks research on any new sustainable model related to its development to tackle the various sustainable development goals and address interactions between them. However, it also clear that such research and approaches are also poorly developed for our current food system. Indeed, the different dimensions of sustainability are rarely analyzed together including for current livestock farming systems. Any new business model should aim to establish positive links between the societal and environmental challenges to the private companies’ economic strategy and interests. This implies for the companies to be able to simultaneously manage tensions between their short-term and the long-term objectives or between different sustainable development goals taken into interactions between them. In any case, however, when we analyze the potential sustainability of the “cultured meat” industry according to recent methodologies and concepts, it is clear that there is a need to confront and juxtapose environmental, health, social, economic and legal issues. So, while “cultured meat” development is highly focused on technical issues, it still lacks integrative approaches to develop sustainable business capabilities.

Going back to the original issues (providing enough food to the world while addressing environmental and animal welfare issues), “cultured meat should be compared to other potential solutions to solve this problem.

Ethics approval

Not applicable

Data and model availability statement

The list of scientific publications discussed in this review is available in Supplementary Material S1. Publications analyzed in this article are also available via a public Zotero group library (https://www.zotero.org/groups/5415123/cultured_meat_2024/library)

Declaration of generative AI and AI-assisted technologies in the writing process

The authors did not use any artificial intelligence assisted technologies in the writing process

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Declaration of interest

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Transparency Declaration

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References

Biscarra-Bellio JC, de Oliveira GB, Marques MCP and Molento CFM 2023. Demand changes meat as changing meat reshapes demand: The great meat revolution. Meat Science 196, 109040.

Bodiou V, Moutsatsou P and Post MJ 2020. Microcarriers for Upscaling Cultured Meat Production. Frontiers in Nutrition 7, 10.

Boler DD and Woerner DR 2017. What is meat? A perspective from the American Meat Science Association. Animal Frontiers 7, 8–11.

Bourdrez V and Chriki S 2022. Qualités nutritionnelle, organoleptique et disposition à payer pour les alternatives à la viande : cas des analogues végétaux, de la « viande in vitro » et des insectes. INRAE Productions Animales 35, 217–236.

Bryant C and Barnett J 2020. Consumer Acceptance of Cultured Meat: An Updated Review (2018-2020). Applied Sciences-Basel 10, 5201.

Bryant C, Szejda K, Parekh N, Desphande V and Tse B 2019. A Survey of Consumer Perceptions of Plant-Based and Clean Meat in the USA, India, and China. Frontiers in Sustainable Food Systems 3, 11.

Chen L, Guttieres D, Koenigsberg A, Barone PW, Sinskey AJ and Springs SL 2022. Large-scale cultured meat production: Trends, challenges and promising biomanufacturing technologies. Biomaterials 280, 121274.

Choudhury D, Tseng TW and Swartz E 2020. The Business of Cultured Meat. Trends in Biotechnology 38, 573–577.

Chriki S, Ellies-Oury M-P, Fournier D, Liu J and Hocquette J-F 2020a. Analysis of scientific and press articles related to cultured meat for a better understanding of its perception. Frontiers in Psychology Eating Behavior 11, 1845.

Chriki S, Ellies-Oury M-P and Hocquette J-F 2020b. Livestock for agro-ecology and sustainable diet. ISBN: 9782855577296.

France Agricole, Paris, France.

Chriki S, Ellies-Oury MP and Hocquette JF 2020c. Viande in vitro - Intérêts, enjeux et perception des consommateurs. Techniques de l'Ingénieur 2020, F6520 V1.

Chriki S, Ellies-Oury M-P and Hocquette J-F 2022. Is "cultured meat" a viable alternative to slaughtering animals and a good comprise between animal welfare and human expectations? Animal Frontiers 12, 35–42.

Chriki S and Hocquette J-F 2020. The myth of cultured meat: a review. Frontiers in Nutrition 7, 7.

Chriki S, Payet V, Pflanzer SB, Ellies-Oury M-P, Liu J, Hocquette É, Rezende-de-Souza JH and Hocquette J-F 2021. Brazilian Consumers' Attitudes towards So-Called "Cell-Based Meat". Foods 10, 2588.

Domigan LJ, Feisst V and Ogilvie OJ 2022. Recipes for cultured meat. Nature Food 3, 9–10.

Doreau M and Corson MS 2017. Production de viande et ressource en eau. Viandes et Produits Carnés 2017, 33-2-1.

Dumont B, Modernel P, Benoit M, Ruggia A, Soca P, Dernat S, Tournadre H, Dogliotti S and Rossing WAH 2020. Mobilizing Ecological Processes for Herbivore Production: Farmers and Researchers Learning Together. Frontiers in Sustainable Food Systems 4, 544828.

Eibl R, Senn Y, Gubser G, Jossen V, van den Bos C and Eibl D 2021. Cellular Agriculture: Opportunities and Challenges. Annual Review of Food Science and Technology 12, 51–73.

FAO 2010. Dietary guidelines and sustainability. Food and Agriculture Organization of the United Nations. Retrieved on 1 February 2022, from *http://www.fao.org/nutrition/education/food-dietary-guidelines/background/sustainable-dietary-guidelines/en/*.

FAO and WHO 2019. Sustainable healthy diets -Guiding principles. FAO/WHO, Rome, Italy.

FAO and WHO 2023. Food safety aspects of cell-based food. FAO/WHO, Rome, Italy.

Fournier T and Lepiller O 2019. Se nourrir de promesses. Enjeux et critiques de l'introduction de deux innovations dans le domaine alimentaire : test nutri-génétique et viande in vitro. Socio. La Nouvelle Revue des Sciences Sociales 12, 73–95.

Fraeye I, Kratka M, Vandenburgh H and Thorrez L 2020. Sensorial and Nutritional Aspects of Cultured Meat in Comparison to Traditional Meat: Much to Be Inferred. Frontiers in Nutrition 7, 35.

Furuhashi M, Morimoto Y, Shima A, Nakamura F, Ishikawa H and Takeuchi S 2021. Formation of contractile 3D bovine muscle tissue for construction of millimetre-thick cultured steak. NPJ Science of Food 5, 6.

Gomez-Luciano CA, de Aguiar LK, Vriesekoop F and Urbano B 2019. Consumers' willingness to purchase three alternatives to meat proteins in the United Kingdom, Spain, Brazil and the Dominican Republic. Food Quality and Preference 78, 103732.

Gousset C, Gregorio E, Marais B, Rusalen A, Chriki S, Hocquette J-F and Ellies-Oury M-P 2022. Perception of cultured "meat" by French consumers according to their diet. Livestock Science 260, 104909.

Guan X, Lei Q, Yan Q, Li X, Zhou J, Du G and Chen J 2021. Trends and ideas in technology, regulation and public acceptance of cultured meat. Future Foods 3, 100032.

Hamlin RP, McNeill LS and Sim J 2022. Food neophobia, food choice and the details of cultured meat acceptance. Meat Science 194, 108964.

Hannan J (Ed) 2020. Meatsplaining: The Animal Agriculture Industry and the Rhetoric of Denial. Sydney University Press, Sydney, NSW, Australia.

Heidemann MS, Maiolino Molento CF, Reis GG and Phillips CJC 2020. Uncoupling meat from animal slaughter and its impacts on human-animal relationships. Frontiers in Psychology 11, 1824.

Hocquette J-F 2015. Is it possible to save the environment and satisify consumers with artificial meat? Journal of Integrative Agriculture 14, 206–207.

Hocquette J-F, Fournier D, Ellies-Oury M-P and Chriki S 2023. Bibliometric analysis of scientific articles related to "cultured meat". Book of Abstracts of the 74th Annual Meeting of the European Federation of Animal Science, 26 August - 1 September 2023, Lyon, France, p. 692.

Hocquette É, Liu J, Ellies-Oury M-P, Chriki S and Hocquette J-F 2022. Does the future of meat in France depend on cultured muscle cells? Answers from different consumer segments. Meat Science 188, 108776.

Iyer RD and Iyer GK 2020. Is Cultured Meat a Viable Alternative to Conventional Meat? Journal of Management and Public Policy 11, 19–27.

Ketelings L, Kremers S and de Boer A 2021. The barriers and drivers of a safe market introduction of cultured meat: A qualitative study. Food Control 130, 108299.

Kombolo Ngah M, Chriki S, Ellies-Oury M-P, Liu J and Hocquette J-F 2023. Consumer perception of "artificial meat" in the educated young and urban population of Africa. Frontiers in Nutrition 10, 1127655.

Laisney C 2016. Vegetarianism and flexitarism, emerging tendencies? How to understand the phenomenon, its evolution in the pass and planning its future? Viandes et Produits Carnés 2016, 32-4–2.

Lee DY, Lee SY, Yun SH, Jeong JW, Kim JH, Kim HW, Choi JS, Kim G-D, Joo ST, Choi I and Hur SJ 2022. Review of the Current Research on Fetal Bovine Serum and the Development of Cultured Meat. Food Science of Animal Resources 42, 775–799.

Li X, Zhang G, Zhao X, Zhou J, Du G and Chen J 2020. A conceptual air-lift reactor design for large scale animal cell cultivation in the context of in vitro meat production. Chemical Engineering Science 211, 115269.

Liu J, Chriki S, Kombolo M, Santinello M, Pflanzer SB, Hocquette É, Ellies-Oury M-P and Hocquette J-F 2023. Consumer perception of the challenges facing livestock production and meat consumption. Meat Science 200, 109144.

Liu J, Hocquette É, Ellies-Oury M-P, Chriki S and Hocquette J-F 2021. Chinese Consumers' Attitudes and Potential Acceptance toward Artificial Meat. Foods 10, 353.

Liu Y, Wang R, Ding S, Deng L, Zhang Y, Li J, Shi Z, Wu Z, Liang K, Yan X, Liu W and Du Y 2022. Engineered meatballs via scalable skeletal muscle cell expansion and modular micro-tissue assembly using porous gelatin micro-carriers. Biomaterials 287, 121615.

Lynch J and Pierrehumbert R 2019. Climate Impacts of Cultured Meat and Beef Cattle. Frontiers in Sustainable Food Systems 3, 1–11.

Mancini MC and Antonioli F 2022. Chapter 19 - The future of cultured meat between sustainability expectations and socio-economic challenges. In Future Foods: Global Trends, Opportunities, and Sustainability Challenges (ed. R. Bhat). Academic Press, Cambridge, MA, USA, pp. 331–350.

Mattick CS, Landis AE, Allenby BR and Genovese NJ 2015. Anticipatory Life Cycle Analysis of In Vitro Biomass Cultivation for Cultured Meat Production in the United States. Environmental Science & Technology 49, 11941–11949.

Messmer T, Klevernic I, Furquim C, Ovchinnikova E, Dogan A, Cruz H, Post MJ and Flack JE 2022. A serum-free media formulation for cultured meat production supports bovine satellite cell differentiation in the absence of serum starvation. Nature Food 3, 74–85.

Morais-da-Silva RL, Reis GG, Sanctorum H and Molento CFM 2022a. The social impacts of a transition from conventional to cultivated and plant-based meats: Evidence from Brazil. Food Policy 111, 102337.

Morais-da-Silva RL, Reis GG, Sanctorum H and Molento CFM 2022b. The social impact of cultivated and plant-based meats as radical innovations in the food chain: Views from Brazil, the United States and Europe. Frontiers in Sustainable Food Systems 6, 1056615.

Moritz J, McPartlin M, Tuomisto HL and Ryynänen T 2023. A multi-level perspective of potential transition pathways towards cultured meat: Finnish and German political stakeholder perceptions. Research Policy 52, 104866.

Moritz MSM, Verbruggen SEL and Post MJ 2015. Alternatives for large-scale production of cultured beef: A review. Journal of Integrative Agriculture 14, 208–216.

Mottet A, de Haan C, Falcucci A, Tempio G, Opio C and Gerber P 2017. Livestock: On our plates or eating at our table? A new analysis of the feed/food debate. Global Food Security 14, 1–8.

Munteanu C, Miresan V, Raducu C, Ihut A, Uiuiu P, Pop D, Neacsu A, Cenariu M and Groza I 2021. Can Cultured Meat Be an Alternative to Farm Animal Production for a Sustainable and Healthier Lifestyle? Frontiers in Nutrition 8, 749298.

Myers GM, Jaros KA, Andersen DS and Raman DR 2023. Nutrient recovery in cultured meat systems: Impacts on cost and sustainability metrics. Frontiers in Nutrition 10, 1151801.

Ng ET, Singh S, Yap WS, Tay SH and Choudhury D 2021. Cultured meat - a patentometric analysis. Critical Reviews in Food Science and Nutrition 0, 1–11.

Nobre FS 2022. Cultured meat and the sustainable development goals. Trends in Food Science and Technology 124, 140–153.

Olenic M and Thorrez L 2023. Cultured meat production: what we know, what we don't know and what we should know. Italian Journal of Animal Science 22, 749–753.

de Oliveira Padilha LG, Malek L and Umberger WJ 2022. Consumers' attitudes towards lab-grown meat, conventionally raised meat and plant-based protein alternatives. Food Quality and Preference 99, 104573.

Ong KJ, Johnston J, Datar I, Sewalt V, Holmes D and Shatkin JA 2021. Food safety considerations and research priorities for the cultured meat and seafood industry. Comprehensive Reviews in Food Science and Food Safety 20, 5421–5448.

Peyraud J-L and MacLeod M 2020. Future of EU livestock: how to contribute to a sustainable agricultural sector? Executive summary. Publications Office of the European Union, Luxembourg, LU.

Poirier N 2022. On the Intertwining of Cellular Agriculture and Animal Agriculture: History, Materiality, Ideology, and Collaboration. Frontiers in Sustainable Food Systems 6, 907621.

Porcher J 2017. The Ethics of Animal Labor - A Collaborative Utopia. Palgrave Macmillan, Cham, Switzerland.

Porcher J 2023. Dossier: Recherches sur la question animale: entre mobilisations sociétales et innovations technologiques– «Slaughter free/Cultured meat». Une morale de marchand. Natures Sciences Sociétés 31, 237-243.

Post MJ and Hocquette JF 2017. New Sources of Animal Proteins: Cultured Meat. In New Aspects of Meat Quality: From Genes to Ethics (ed. P.P. Purslow). Woodhead Publishing Series in Food Science Technology and Nutrition, Cambridge, UK, pp. 425–441.

Post MJ, Levenberg S, Kaplan DL, Genovese N, Fu J, Bryant CJ, Negowetti N, Verzijden K and Moutsatsou P 2020. Scientific, sustainability and regulatory challenges of cultured meat. Nature Food 1, 403–415.

Pulina G, Lunesu MF, Pirlo G, Ellies-Oury M-P, Chriki S and Hocquette J-F 2022. Sustainable production and consumption of animal products. Current Opinion in Environmental Science & Health 30, 100404.

Risner D, Kim Y, Nguyen C, Siegel JB and Spang E 2023. Environmental impacts of cultured meat: A cradle-to-gate life cycle assessment. bioRxiv, 2023–04.

Rodríguez Escobar MI, Cadena E, Nhu TT, Cooreman-Algoed M, De Smet S and Dewulf J 2021. Analysis of the Cultured Meat Production System in Function of Its Environmental Footprint: Current Status, Gaps and Recommendations. Foods 10, 2941.

Ryschawy J, Dumont B, Therond O, Donnars C, Hendrickson J, Benoit M and Duru M 2019. An integrated graphical tool for analysing impacts and services provided by livestock farming. Animal 13, 1760–1772.

Shapiro P 2018. Clean Meat: How Growing Meat Without Animals Will Revolutionize Dinner and the World. Science 359, 399.

Siegrist M and Hartmann C 2023. Why alternative proteins will not disrupt the meat industry. Meat Science 203, 109223.

Sijpestijn GF, Wezel A and Chriki S 2022. Can agroecology help in meeting our 2050 protein requirements? Livestock Science 256, 104822.

Sinke P, Swartz E, Sanctorum H, van der Giesen C & Odegard I 2023. Ex-ante life cycle assessment of commercial-scale cultivated meat production in 2030. International Journal of Life cycle Assessment 28, 234–254.

Smetana S, Mathys A, Knoch A and Heinz V 2015. Meat alternatives: life cycle assessment of most known meat substitutes. International Journal of Life Cycle Assessment 20, 1254–1267.

Stephens N 2021. Join our team, change the world: edibility, producibility and food futures in cultured meat company recruitment videos. Food, Culture & Society 0, 1–17.

Thorrez L, DiSano K, Shansky J and Vandenburgh H 2018. Engineering of human skeletal muscle with an autologous deposited extracellular matrix. Frontiers in Physiology 9, 1076.

Treich N 2021. Cultured meat: Promises and challenges. Environmental & Resource Economics 79, 33–61.

Tuomisto HL, Allan SJ and Ellis M.J. 2022. Prospective life cycle assessment of a bioprocess design for cultured meat production in hollow fiber bioreactors. Science of The Total Environment 851, 158051.

Tuomisto HL, Ellis MJ and Hasstrup P 2014. Environmental impacts of cultured meat: alternative production scenarios. In Proceedings of the 9th International Conference on Life Cycle Assessment in the Agri-Food Sector (ed. R. Schenck, D. Huizenga). ACLCA, Vashon, WA, USA, pp. 1360-1366. JRC91013.

Tuomisto HL and de Mattos MJT 2011. Environmental Impacts of Cultured Meat Production. Environmental Science & Technology 45, 6117–6123.

Zhang L, Hu Y, Badar IH, Xia X, Kong B and Chen Q 2021. Prospects of artificial meat: Opportunities and challenges around consumer acceptance. Trends in Food Science & Technology 116, 434–444.

Table 1: Main stages or events in the development of ″cultured meat″.

Year	Main stages or events
1912	Demonstration by the French biologist Alexis Carrel that maintaining muscle tissue outside the body is possible
1932	Winston Churchill's criticism of the *“absurdity of growing a whole chicken to eat the breast or wing' and the possibility of 'growing these parts separately in a suitable medium”.*
1932	First patent to produce laboratory meat by Willem van Eelen
2012	Launch of "Modern Meadow", a company wishing to produce cultured leather and "cultured meat".
2013	Highly- publicized presentation in London of the first artificial meat burger by Professor Mark Post of Maastricht University.
2014	Launch of New Harvest (an organization promoting "cultured meat"), but also of Muufri and Clara Foods (companies planning to produce cultured dairy products and eggs respectively) and Real Vegan Cheese (a non-profit organization developing a research project on the creation of “cultured cheese”).
2016	Launch by “Mercy For Animals” of the Good Food Institute, which is a non-profit organization for the promotion of plant- and cell-based alternatives to animal products.
2019	Launch of the alliance for Meat, Poultry & Seafood Innovation (AMPS Innovation) as the first industry collation of important “cultured meat” players.
2020	Approval by the state of Singapore of the marketing of "cultured meat".
2021	Launch of the Cellular Agriculture Europe association.
2022	The food sustainability award delivered to Aleph Farms from the Academia for a Better World, co-founded by Better World Fund and University of Paris-Saclay.
2022	First recognition by the Food Drug Agency of the positive claims by Upside Foods of their ″cultured meat” produced in the United States.
2022	Expert consultation by FAO on food safety issues related to cell-based food.
2023	Approval for their "cultured meat" labels from the USDA's Food Safety and Inspection Service to two "cultured meat" companies (Good Meat and Upside Foods).
2023	Approval in the European Union to a Czech start-up Bene Meat Technologies for the commercialisation of its "cultured meat" for pet food.
2024	Approval in Israel to Alephs Farm for the commercialisation of its "cultured meat".
2024	A dozen European countries (including Italy, France and Austria) or a few American states (Alabama, Florida) wish to ban “cultured meat”.

Table 2: Top 10 keywords, searched terms, journals, thematic (Web of Science Categories)

	Top 10 Author keywords	Top 10 Journals	Top 10 Web of Science Categories
1	Cultured meat (337)	Foods (41)	Food Science & Technology (387)
2	Cultivated meat (78)	Frontiers in Sustainable Food Systems (33)	Nutrition & Dietetics (87)
3	Cellular agriculture (70)	Fleischwirtschaft (27)	Biotechnology & Applied Microbiology (67)
4	In vitro meat (64)	Food Research International (26)	Environmental Sciences (63)
5	Sustainability (47)	Meat Science (26)	Engineering, Biomedical (58)
6	Tissue engineering (46)	Appetite (25)	Multidisciplinary Sciences (58)
7	Meat (37)	Food Quality and Preference (23)	Materials Science, Biomaterials (54)
8	Cell-based meat (33)	Trends in Food Science & Technology (23)	Agriculture, Dairy & Animal Science (53)
9	Clean meat (31)	Tissue Engineering Part A (22)	Cell Biology (51)
10	Alternative proteins (30)	Frontiers in Nutrition (19) Sustainability (23)	Environmental Studies (45)

Table 3: Top 10 prolific countries, institutions, authors in cultured meat field

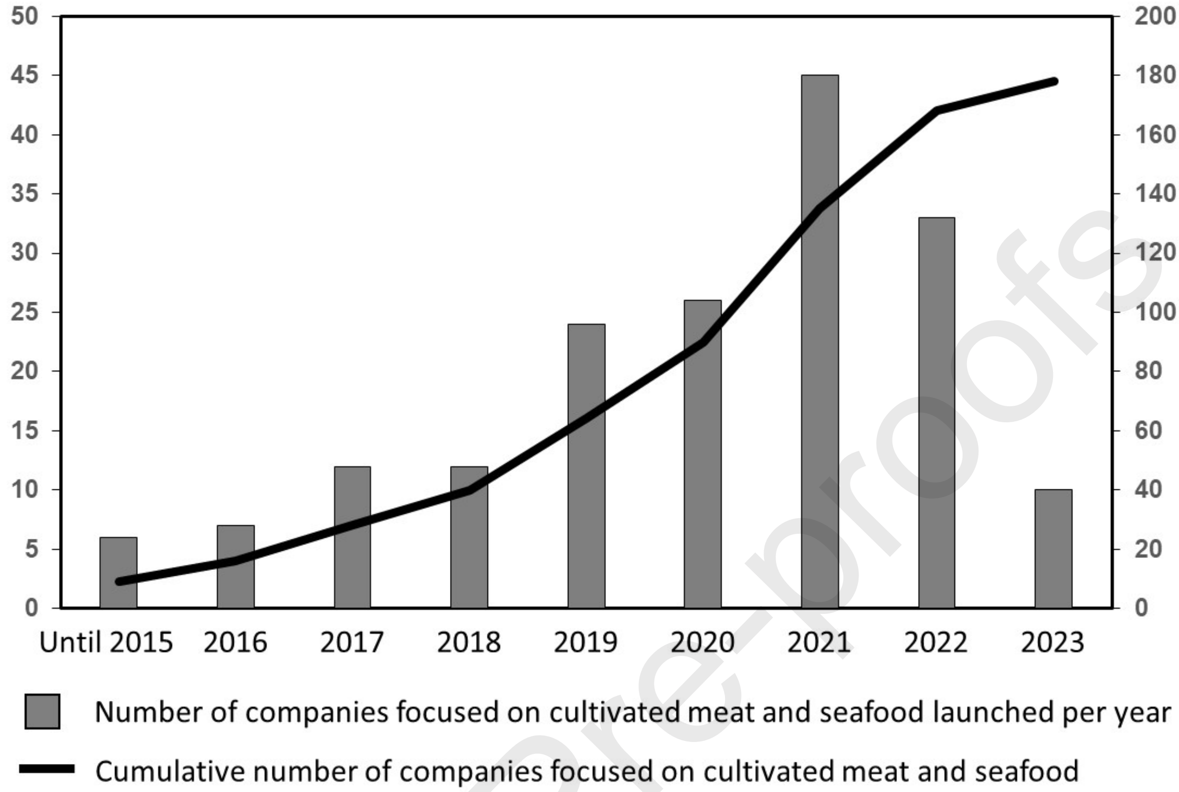
Ranking	Top 10 countries	Top 10 Institutions	Top 10 Authors
1	USA (217)	INRAE (32)	Post MJ (21)
2	China (114)	Nanjing Agricultural University (27)	Ding SJ (20)
3	United Kingdom (95)	University of California System (26)	Hocquette JF (20)
4	South Korea (66)	Maastricht University (24)	Kaplan DL (19)
5	Germany (64)	Jiangnan University (21)	Zhou GH (17)
6	Netherlands (62)	Tufts University (21)	Zhou JW (16)
7	Australia (49)	University of Bath (22)	Shimizu T (15)
8	Japan (44)	Vetagro Sup (20)	Park S (14)
9	France (42)	Wageningen University Research (20)	Chriki S (12)
10	Singapore (37) Canada (37)	Agency for Science Technology Research A Star (19) Seoul National University SNU (19) University of Bath (19)	Du GC (12) Takeuchi S (12)

Figure captions

Figure 1: Number of companies focused on “cultured meat” and “cultured seafood” launched per year since 2015 (left scale) and total number of companies focused on “cultured meat” and “cultured seafood” (right scale). Source: https://gfi.org/resource/cultivated-meat-eggs-and-dairy-state-of-the-industry-report/

Figure 2: Number of scientific publications about “cultured meat” per year since 2015 (left scale) or in total (right scale).
This figure is based on data extracted from the Science Citation Index Expanded (SCI-EXPANDED) database of the Web of Science (WoS) Core Collection database from Clarivate Analytics (Date last update 22 February 2024). We searched for articles containing the same keywords as in *Chriki et al (2020b).*

Figure 1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Number of companies focused on cultivated meat and seafood launched per year
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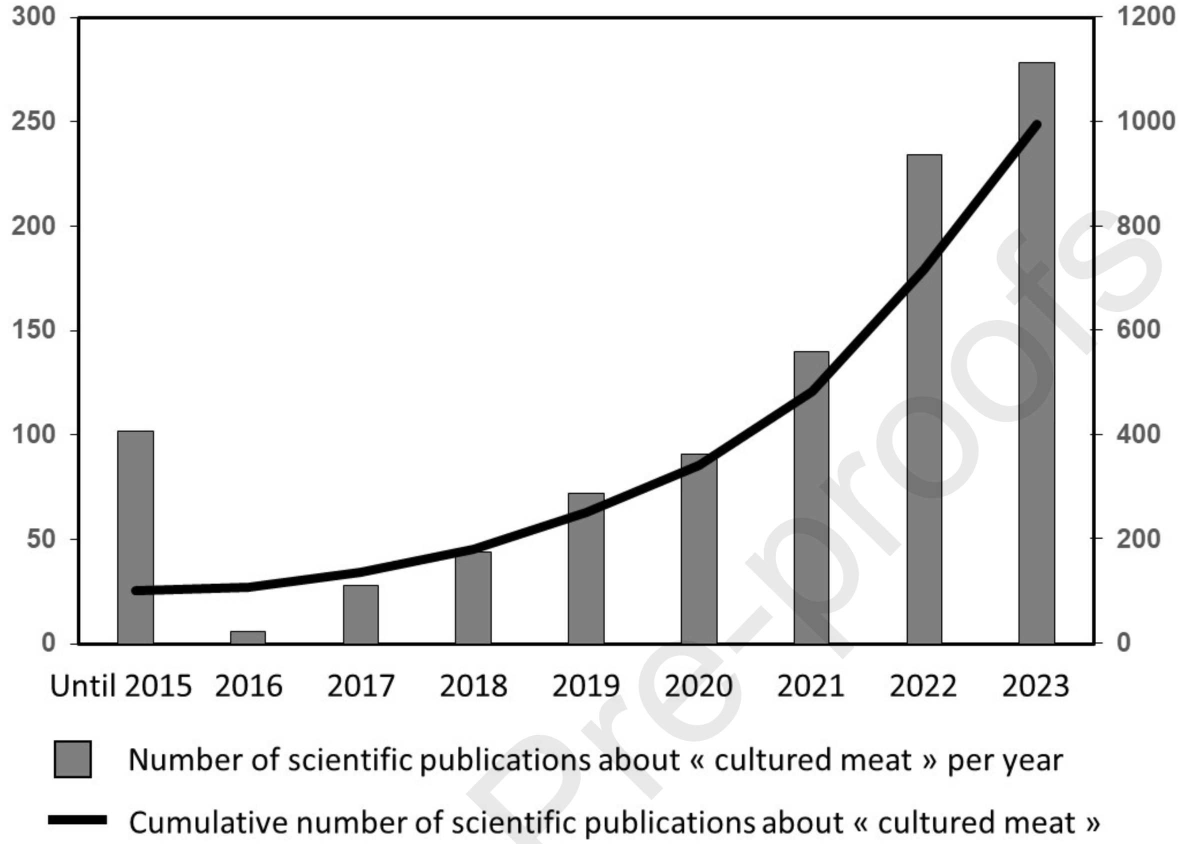
Figure 2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Number of scientific publications about « cultured meat » per year
Cumulative number of scientific publications about « cultured meat »

Author contributions

AUTHOR CONTRIBUTIONS

Jean-François Hocquette, Marie-Pierre Ellies-Oury and Sghaier Chriki first discussed the content of the manuscript and provided key scientific papers to consider.

Dominique Fournier conducted the bibliometric analysis

Jean-François Hocquette wrote the first draft

Marie-Pierre Ellies-Oury and Sghaier Chriki edited the first draft

All authors approved the final version