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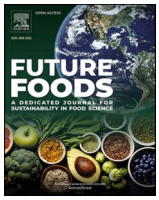

Hypothetical feed conversion efficiency of cultured meat compared to conventional animal production

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ABSTRACT

The pressure on agro-livestock systems calls for a critical review of production systems focusing on efficiency and sustainability. Cultured meat (CM) emerges as an alternative production but requires comparable parameters for evaluation. This paper proposes a hypothetical reformulation of the concept of Feed Conversion Rate (FCR) and Edible Meat ConversionRate (EMCR), traditionally employed in animal-derived food production, by adapting it to the context of cellular agriculture, in particular to CM. After an analysis of the FCR in the main conventional sectors (poultry, swine, cattle and fish), used for the calculation of EMCR, a theoretical model was developed for the calculation of the Cultured Meat Conversion Ratio (CMCR), based on the chemical composition of the culture media. The estimated CMCRs (0.316–0.687) and the CMCR on a dry matter basis for CM (2.29) were lower than those reported for traditional animal supply chains, indicating a potentially higher theoretical efficiency. However, these estimates do not account for the specific resources required to produce the ingredients of the culture medium, the actual metabolic efficiency of the cells, the accumulation of toxic metabolites (e.g., ammonia, lactate), nor the potential impact of future media formulations based on alternatives to foetal bovine serum. Although a theoretical calculation, this study provides a useful conceptual framework for the definition and optimisation of FCR in alternative cell culture systems, laying the basis for the development of reliable metrics in cellular agriculture and comparative evaluation between innovative and conventional food systems.

1. Introduction

The steady growth of the world population, currently estimated at around 8 billion people, is expected to reach 11 billion by 2100 (Fig. 1), exerting significant pressure on global food systems (Roser and Ritchie, 2023).

Consequently, over the years, the agri-food sector has had to adapt and evolve to ensure an adequate supply of essential foods. In particular, as reported by FAO (2021), and depicted in Table 1, the demand for animal-derived food-products has increased dramatically over the past 50 years.

This trend, as described by Bellet and Rushton (2019) and Rubio et al. (2019), will be even more evident in the future. In particular, global meat consumption is expected to reach 455 million tonnes by 2050, an increase of 76% from 2005 levels. In parallel, global demand for aquaculture sector will reach 140 million tonnes by 2054 (Bellet and Rushton, 2019; Rubio et al., 2019). For this reason, today's livestock systems have faced profound changes, undergoing a process of intensification to satisfy an ever-increasing demand. As shown in Table 2, the livestock population (cattle, sheep, goats, pigs and poultry) is set to increase over the coming decades (Yitbarek, 2019; Statista, 2025; Statista, 2025a; World population review, 2025).

It is easy to understand how these growths and projections have been caused and will continue to cause great pressure on the production of the animal feed sector, the main driver of the livestock industry. Currently, as reported by Makkar (2018), about 800 million tonnes of cereals (about one third of total production) are destined for animal feed, rising to over 1.1 billion tonnes by 2050. The data just reported reveal an alarming problem: the feed/food competition, defined as *'the tensions and trade-offs between using edible crops and other resources to either feed people directly or feed livestock'* (Breewood and Garnett, 2020).

Although livestock production plays a crucial role in transforming plant resources into food products of high biological value, it is characterised by well-documented inefficiencies (Fry et al., 2018). Indeed, about 36% of global crop-derived energy (equivalent to 1.43×10^{13} GJ) are used for livestock feed, but only 12% of these are actually converted

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into food for human consumption (Fry et al., 2018). This scenario becomes even more relevant in light of global population growth, highlighting the urgency of developing strategies to optimise the efficiency of food and feeding systems (Wilkinson, 2011).

Among the emerging alternatives in the food production landscape, cellular agriculture, and Cultured Meat (CM) in particular, holds a prominent position, attracting increasing interest from scientific research. The term '*cellular agriculture*' refers to an innovative technology that enables the production of food, such as meat, fish and dairy products, from individual cells instead of whole organisms (Rischer et al., 2020). Its main goal is to obtain products with a molecular composition and nutritional characteristics similar to those of their traditional counterparts (Eibl et al., 2021). In this context, CM (also referred for fish meat) is produced through the *in vitro* differentiation of muscle satellite cells (stem cells), without the need to breed and slaughter animals. This process is based on tissue engineering techniques, enabling the generation of skeletal muscle tissue (Eibl et al., 2021). Although the literature describes CM as potentially more sustainable, safe and efficient than traditional methods, comparisons with the conventional food system are often inaccurate and sometimes misleading (Chriki & Hocquette, 2020). However, it is important to emphasise, once again, that the continued growth of the world population in the coming decades will require an increase in global food production (Roser and Ritchie, 2023; Lanzoni et al., 2024). In this context, livestock will continue to play a key role due to their ability to efficiently convert non-edible resources for humans - such as grass, fodder and co-products of the food industry - into high-quality, nutritionally valuable goods (Malenica et al., 2022). In our opinion, a comparative analysis between CM and conventional systems should extend beyond just environmental metrics, including key parameters such as Feed Conversion Ratio (FCR) and Edible Meat Conversion Rate (EMCR), in order to offer a more complete and balanced evaluation.

In light of the current challenges related to the sustainability of food systems, this review aims to critically analyse the FCR and EMCR in the main traditional livestock systems, while introducing an operational definition of conversion efficiency applicable to CM. The objective is to provide a more robust and consistent comparative framework that can support scientifically based assessments of the efficiency of different production models. This approach aims to promote more rigorous and evidence-based comparisons, contributing to a clearer understanding of the potential and limitations of emerging alternatives to conventional livestock production. In particular, this work aims to: (i) Derive typical FCR and EMCR values for meat production from poultry, pigs, cattle and fish from the literature, including an analysis of the main factors influencing the variability of these values; (ii) Develop a new model to define equivalent FCR values for CM defined as Cultured Meat Conversion Ratio (CMCR) and evaluate the factors that may influence its conversion efficiency; (iii) Compare the values obtained for livestock with those for cell culture, discussing the validity of these comparisons and identifying aspects that need further investigation to improve the robustness of the comparative analyses.

2. The concept of efficiency

Efficiency in livestock production represents the ability of animals to optimally convert the resources used (feed, water, soil and energy) into valuable products such as meat, milk and eggs. One of the most significant indicators is feed conversion efficiency, which expresses the amount of feed required to obtain one unit of product (Wilkinson, 2011). Next to this parameter, water use efficiency plays a central role, as it measures the volume of water consumed per kilogram of product (Kebebe et al., 2015). In general, poultry and pig supply chains have a lower water footprint than cattle (Ritchie, 2020). Land use efficiency is also a determining factor: it considers the area required to rear animals and cultivate the raw materials for their feed. Although intensive systems require less land, they raise important issues of animal welfare and environmental impact (Moekti, 2020). This is compounded by the assessment of greenhouse gas emissions per unit of output: ruminants, such as cattle, produce higher amounts of methane, resulting in higher emission intensity than monogastric animals, such as chickens and pigs (Ritchie, 2020). Livestock efficiency also includes biological aspects - such as growth rates, milk production and fertility - as well as economic factors, defined as the ratio between the value of the products obtained and the cost of the inputs used (Chetroiu and Iurchevici, 2024). The improvement of these parameters is based on integrated strategies: targeted genetic selection (Madilindi et al., 2022), effective health

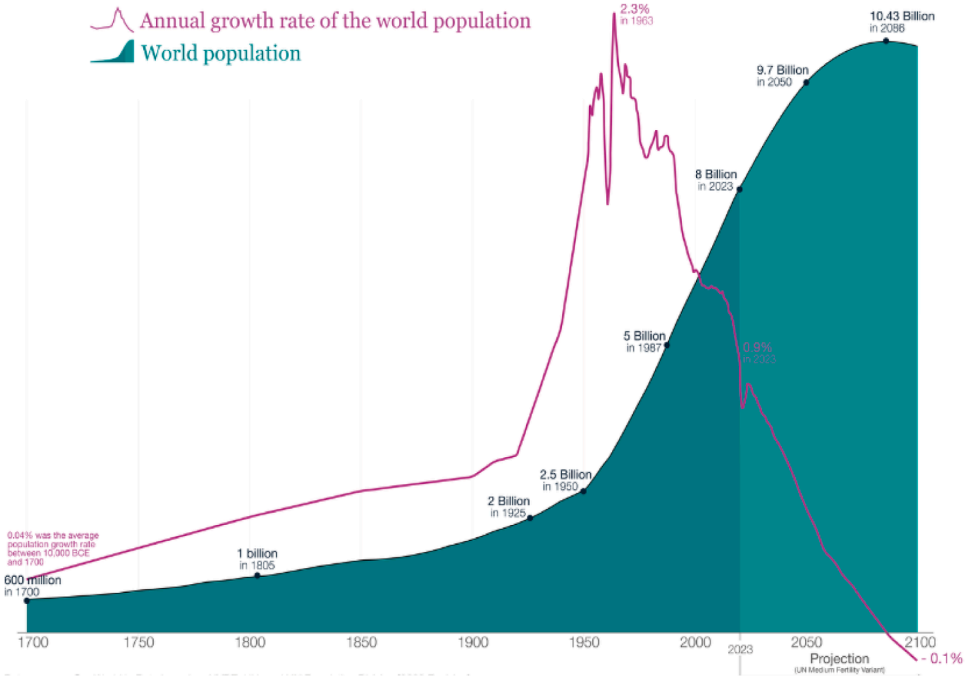

Fig. 1. World population growth from 1700 to 2100 (Roser and Ritchie, 2023).

management (Jarvis and Valdes-Donoso, 2018), appropriate breeding conditions (Ramirez et al., 2022), the use of precision livestock farming technologies (Papakostantinou et al., 2024) and, above all, the formulation of balanced and functional diets. From this perspective, animal nutrition plays a central role in resource optimisation, contributing significantly to increased productivity and the overall sustainability of livestock systems (Barszcz et al., 2024).

In the concept of efficiency, FCR defines how efficiently an animal converts feed into body mass:

$$\text{FCR} = \text{Feed intake (kg)}/\text{Body weight gain (1 kg)}$$

Specifically, the FCR is a key parameter in animal husbandry and aquaculture, used to assess the efficiency with which an animal converts feed into body weight (1 kg of animal food product). It is defined as the ratio between the amount of feed consumed and the weight gain of the meat-producing animal over a given period (Wilkinson, 2011). However, since FCR is based on the increase in total body weight, which includes both edible and inedible components, it can lead to an inaccurate estimate of feed efficiency when compared to CM, where the entire biomass is presumably edible. To overcome this problem, we calculate the EMCR by adjusting the traditional FCR according to the percentage of edible meat obtained from the animal carcass:

$$\text{EMCR} = \text{FCR}/\text{Edible meat yield fraction}$$

In cell cultures, cells utilise their metabolism to synthesise macromolecules from the stimuli and nutrients provided by the culture medium (Fig. 2). It therefore becomes essential to precisely define the efficiency of cells in generating edible biomass. To this end, the CMCR, a parameter expressing the efficiency with which cultured cells convert nutrients into edible biomass for food consumption, has been proposed.

$$\text{CMCR} = \text{Nutrient input mass}/\text{Edible biomass produced}.$$

Nutrient input refers to the total mass (or energy content) of the media components used, while edible biomass is the mass of muscle tissue harvested (wet or dry weight). As anticipated, this formula allows for the comparison of efficiency across different culture methods, types of growth media, and production scales. Furthermore, when properly normalized, it will enable broader comparisons with conventional livestock farming systems.

3. Meat production cycle duration across different sectors

The production cycle type and duration are key factors influencing the FCR in livestock production. The FCR can be influenced by both the length and management of the production cycle. FAO (1995) identified three main types of livestock production systems: grazing, mixed, and industrial. Grazing systems are characterized by low animal stocking densities per hectare and contribute approximately 9% of global meat production (Gerbens-Leenes et al., 2013). Although the term suggests that animals feed exclusively on pasture, in practice, their diets often include grains, legumes, and oilseed by-products. Mixed systems combine livestock and crop production, with most of the animal feed being produced on the same farm. These systems are widespread globally and represent the predominant model of cattle farming in countries such as Brazil, China, Ethiopia, India, New Zealand, and the United States (Gerbens-Leenes et al., 2013). They account for about 54% of global meat production and 90% of milk production. Industrial systems, on the other hand, are characterized by high animal stocking densities and produce less than 10% of feed on-site. This model is dominant for cattle in regions such as Japan and Western Europe and represents the primary system for pig and poultry meat production in most parts of the world (Gerbens-Leenes et al., 2013).

Table 2
Projection of livestock population from 2020 up to 2050 in four decades. Values are reported in billions (Yitbarek, 2019; Statista, 2025; Statista, 2025a; World population review, 2025).

Livestock	2020	2030	2040	2050
Cattle	1.520	2.423	2.593	2.636
Sheep and Goat	2.4	2.566	2.677	2.939
Pigs	0.780	1.121	1.076	1.141
Poultry	24.760	28.819	32.423	37.030

In general, longer production cycles are associated with reduced feed efficiency, as slower growth rates tend to increase the FCR. Animals that require more time to reach market weight consume greater quantities of feed over their lifetime; if growth performance is not optimised, this extended feeding period results in a higher FCR and diminished overall efficiency (Aviagen, 2022). Conversely, shorter cycles, typical of intensive production systems, can reduce feed intake relative to body weight gain, thus improving FCR. However, it is crucial to emphasise that multiple other parameters such as general animal health status, feed quality and environmental stressors play a significant role in determining FCR (Coleman and Moore, 2003; Besson et al., 2016; Stass, 2019). In this context, CM production is probably characterised by a significantly shorter production cycle (Ding et al., 2021) than that of the traditional sectors (chicken, pork, beef and fish), as illustrated in Fig. 3.

Poultry: The Ross 308 is the most popular fast-growing hybrid in the poultry industry. According to Aviagen (2022), the rearing period can extend up to 56 days, although slaughtering commonly takes place between 35 and 42 days (Khan et al., 2010; Vispute et al., 2019; Martinez and Valdivie, 2021). In contrast, breeds that have not undergone intense genetic selection generally have a longer production cycle, resulting in a production chain with longer time frames.

Pig: In the pig sector, the duration of the production cycle typically ranges from 6 to 24 months, depending on the breed used. The most common pig breeds worldwide for pork production are the Large White (accounting for over 50% of the global genetic stock), originally from the United Kingdom, followed by Landrace and Duroc. The Large White is valued for its versatility and high productivity. In particular, the Duroc breed, renowned for its high slaughter yield, can be processed for meat as early as six months of age, making it one of the earliest maturing breeds (Fàbrega et al., 2013). Pigs also play a central role in the production of cured meats, especially in Italy, where the heavy pig supply chain is primarily focused on the production of high-end raw hams with Protected Designation of Origin (PDO), such as Prosciutto di Parma and Prosciutto di San Daniele. However, although Duroc pigs are commonly slaughtered at six months of age, the Italian Duroc, as well as Italian Large White, Italian Landrace, and their crossbreeds, must be slaughtered at a minimum age of nine months, as established by Consorzio del Prosciutto di Parma (2023) and Consorzio del Prosciutto San Daniele (2023). This period may be extended further to ensure optimal

Table 1
Consumption (kg/person/year) of animal derived food-products for Europe, China, North America and Africa in 1961 and 2020. Table adapted by FAO (2021).

	Europe		China		N. America		Africa	
	1961	2020	1961	2020	1961	2020	1961	2020
Meat	47.24	75.82	3.35	61.89	74.24	100.72	13.32	16.46
Milk	171.2	182.3	2.37	25.02	220.80	169.13	29.96	27.22
Fish	13.85	21.77	4.33	11.33	11.33	18.28	4.57	9.58
Eggs	8.96	13.90	2.06	14.44	14.44	15.78	1.24	2.14

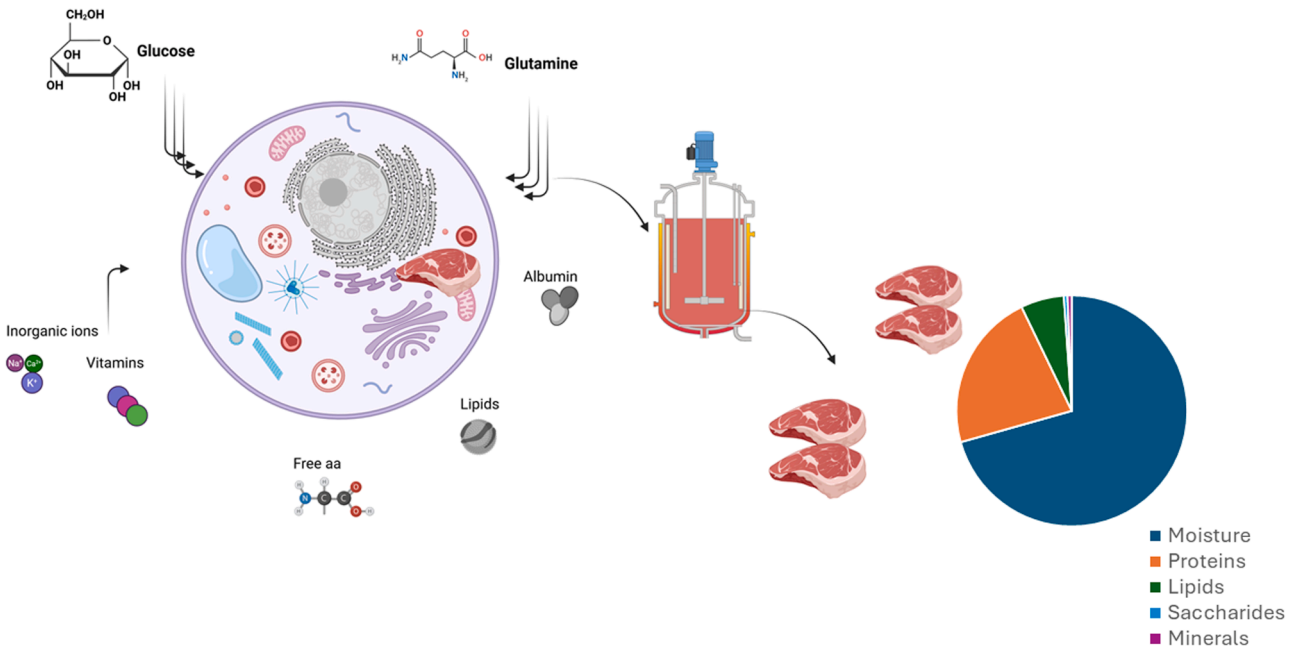

Fig. 2. Nutrients requirement for mammalian cell growth/proliferation and hypothetically derived cellular meat composition. The major contributors towards the synthesis of cellular macromolecules are indicated. The Figure was created using Biorender.com.

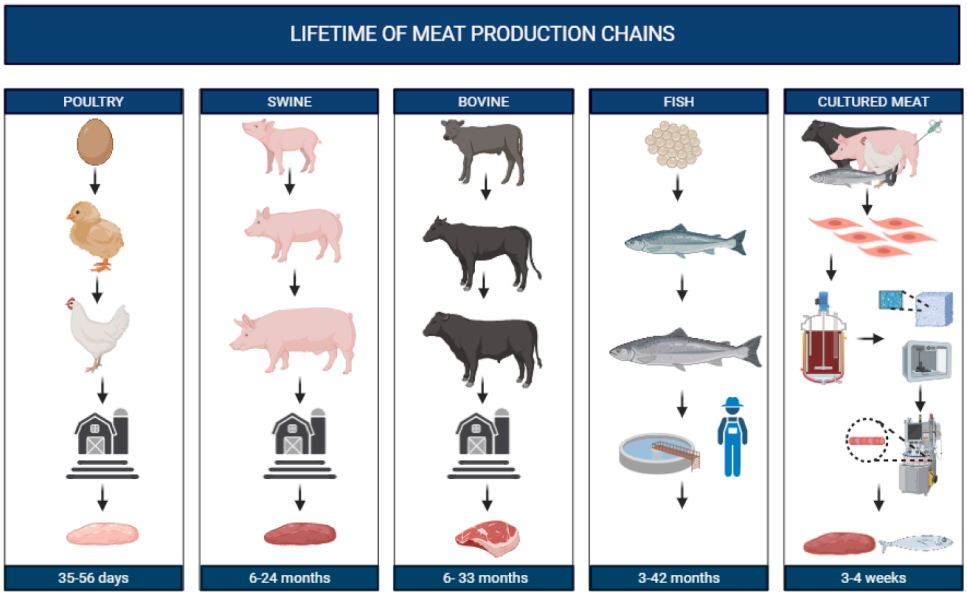

Fig. 3. Lifetime of different meat production chains (poultry, swine, bovine, fish and cultured meat). The Figure was created using Biorender.com.

technological yield and to develop the desired sensory qualities of the meat during the curing process, which lasts at least 12 months (Bosi and Russo, 2004). In the European context, the pig breed with the longest production cycle is the Hungarian Mangalica, which is characterised by slow growth and is slaughtered at approximately 24 months of age (Egerszegi et al., 2003).

Cattle: Fig. 3 shows how the length of the cattle supply chain can vary widely, ranging from 6 to 33 months. This wide variability is determined by several factors, including the characteristics of the breeds reared and the specific production steps that contribute to the supply chain. Each breeding system, in fact, follows different strategies based on the production objectives, the commercial destination of the meat and the breeding conditions adopted. The shortest production cycle is represented by the calf, the definition of which is regulated by EFSA (2023) and Council Directive 2008/119/EC (European Union, 2017), which identify as '*calves*', cattle no older than six months. This category constitutes the fastest supply chain in the cattle sector, as the product is obtained from animals reared for a relatively short period of time, with specific nutritional practices that influence the quality characteristics of the meat. However, the duration of the beef supply chain can extend significantly depending on the breed and farming system adopted. Some beef breeds, for example, require a longer growth period to reach the desired weight and characteristics before slaughter, as illustrated in Table 3.

Fish: Aquaculture contributes significantly to food supply, surpassing both wild-caught fish and beef in terms of weight. In particular, world production of fisheries and aquaculture reached 223.2 million tonnes in 2022, 185.4 million tonnes of aquatic animals and 37.8 million tonnes of

Table 3
Slaughter age (days) of different cattle breeds. Table modified from Hozáková, et al. (2020).

Cattle breed	Slaughter age (days)	Reference
Aberdeen angus	597.7	Alberti et al. (2008)
	433.7	Bartoň et al. (2006)
	381	Chambaz et al. (2003)
	510	Bureš and Bartoň (2018)
Charolaise	634	Alberti et al. (2008)
	526.3	Bartoň et al. (2006)
	513	Chambaz et al. (2003)
	630	Hozáková et al. (2020)
Simmental	621.8	Alberti et al. (2008)
	515.5	Bartoň et al. (2006)
	499	Chambaz et al. (2003)
Holstein	596.3	Alberti et al. (2008)
	515	Bureš and Bartoň (2018
Limousine	594	Chambaz et al. (2003)
Belgian Blue	648	Fiems et al. (2003)
Chianina	548-761	Ranucci et al. (2002)
	548-639	Preziuso and Russo (2004)
Piemontese	457-548	Anaborapi (2025)
	396-427	Anaborapi (2025)
Wagyu	852-1004	Gotoh et al. (2018)

algae (FAO, 2024). In 2021, aquatic animal foods accounted for 15 % of global animal protein consumption and 6 % of total protein intake. For 3.2 billion people, these foods contributed at least 20 % of their per capita intake of animal-derived protein (FAO, 2024). As reported by Fry and colleagues (2018), aquaculture is a highly heterogeneous sector in terms of species farmed and production techniques, which is why this section will consider the fish species most commonly used in cell agriculture. According to Goswami et al. (2022) and Feddern et al. (2024), the main companies involved in cultivated seafood production focus on species such as white fish, bluefin tuna and Atlantic salmon. Among the white fish species, tilapia is of the most important. Originating from Africa and the Middle East, tilapia has become one of the most widespread and commercially relevant fish species globally (Gupta and Acosta, 2004). As reported by Wang and Lu (2016), depending on farming techniques, the production cycle of tilapia can vary between 90 and 240 days, thus confirming it as a relatively fast supply chain for obtaining fish with valued characteristics and a good nutritional profile. In parallel, the catfish is a freshwater species particularly adapted to confined environments, with a remarkable resistance to handling and disease (Abdel-Mobdy et al., 2021). Among the various catfish species, the most reared is the Amur catfish (*Silurus asotus*), contributing 0.62% of the total aquaculture production, followed by the Channel catfish (*Ictalurus punctatus*), the Pangasius (*Pangasius hypophthalmus*) and the African catfish (*Clarias gariepinus*), which contribute 0.53%, 0.52% and 0.33%, respectively (Dauda et al., 2018). In particular, as pointed out by Ching (2023), rearing *S. asotus* fish to an edible size of 500 g generally takes 6 to 9 months, depending on growth conditions, environmental conditions and management practices adopted. In contrast, production chains for species such as Atlantic bluefin tuna (*Thunnus thynnus*) and Atlantic salmon (*Salmo salar*) take longer. Atlantic bluefin tuna is one of the species with the highest commercial value, supporting the tuna aquaculture industry in the Mediterranean Sea. Farming of this species is a seasonal activity that involves catching wild fish and rearing them in sea cages for periods ranging from 3 months to 2 years (Mylonas et al., 2010). According to the International Commission for the Conservation of Atlantic Tunas (2008), Atlantic bluefin tuna farming operations are classified as '*fattening*' when they last from 3 to 7 months and involve mature fish (weighing more than 30 kg), and as '*farming*' when the duration is longer, up to 2 years, and involves young fish (weighing between 8 and 30 kg). With regard to Atlantic salmon, according to the FAO (2025), rearing generally lasts between 2 to 3 years, comprising an initial freshwater phase lasting 12 to 18 months, during which the fry develop into smolts. This is followed by a saltwater phase lasting between 12 and 24 months, until the salmon reach commercial size. Therefore, the total rearing time can vary between 24 and 42 months, depending on environmental conditions and management practices.

As described above, the duration of the different production chains is characterised by similar (in the case of poultry meat) or significantly longer times than in cellular agriculture, particularly in the production of CM. This disparity can be attributed to the specifics of the production process typical of this innovative technology (Fig. 4).

The CM production process, as illustrated in Fig. 4, can be divided into four main stages: cell harvest from an animal source, cell proliferation, differentiation and maturation (Lanzoni et al., 2022; Manzoki et al., 2024). The initial phase involves the collection of cells from a healthy animal through a biopsy. Generally, young, male animals bred under extensive conditions are preferred, as these factors are associated with a higher presence of satellite cells (adult skeletal muscle stem cells), which are crucial for ensuring a high regenerative and proliferative capacity of muscle tissue (Vestergaard et al., 2000; Choi et al., 2021; Melzener et al., 2021). Subsequently, the selected cells are transferred to a dedicated bioreactor for proliferation, a controlled environment in which optimal conditions for cell growth are provided. The aim of this phase is to achieve the highest possible cell density, which is necessary to ensure efficient production (Manzoki et al., 2024). Considering an average duplication time between 24 and 40 hours for myogenic and adipogenic cells, it is estimated that approximately 4 days are required to reach a final cell density of 10^7 cells/mL, which is considered optimal according to Hubalek et al. (2022) and Manzoki et al. (2024). Once an adequate cell density has been achieved, the cells are transferred to a second bioreactor to start the differentiation and maturation phase. During this phase, the cells are generally grown on a solid matrix (scaffold), which provides the structural support necessary to facilitate their organisation into a three-dimensional tissue (Post et al., 2020). Compared to the proliferation phase, the differentiation process takes significantly longer, which varies according to the cell type involved. In particular, adipogenic cells require a differentiation period approximately seven times longer than that required for proliferation (Moutsatsou et al., 2023), making this phase one of the most critical in CM production. Finally, maturation represents the last crucial step in the production process of CM, where the myotubes, i.e. the already differentiated muscle cells, are transferred into dedicated bioreactors to acquire a more complex and functional structure, able to reproduce the biomechanical, biochemical and sensory characteristics of conventional meat, such as texture, flavour and taste (Kantono et al., 2022). Currently, limited data are available on the exact duration of this phase.

Therefore, although Ding et al. (2021) estimate a production time of about 3-4 weeks to obtain a complete CM product, the validity of this prediction will have to be confirmed on an industrial scale. Only through large-scale application will it be possible to obtain more accurate data, allowing a rigorous evaluation and reliable comparison with traditional production chains.

4. FCR of main livestock systems

The livestock sector is strongly focused on reducing the FCR, a key parameter whose decrease reflects greater efficiency in feed utilisation and hence food production. This objective has been pursued with particular success in broiler production, where a profound improvement in industrial productivity has been achieved through intensive genetic selection (Zuidhof et al., 2014; Aviagen, 2022), supported by a crucial role of the feed industry, which is committed to the valorisation of feed materials capable of sustaining the high production performance of animals. As highlighted by Barszcz et al. (2024), nutrition represents the main environmental factor influencing the development, health status, growth performance and, consequently, profitability of poultry farming.

In particular, as shown in Table 4, the virtuous interaction between genetics and nutrition led to a substantial improvement in FCR in broiler chicken between 1957, 1978 and 2005.

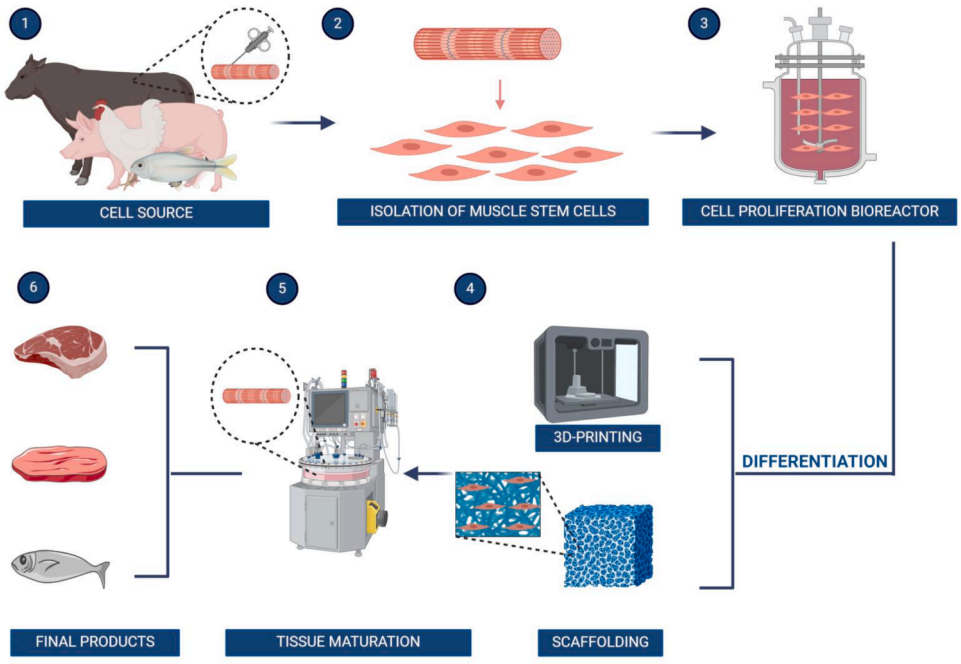

Fig. 4. Cultured meat production process. Figure adapted from Lanzoni et al. (2022). The Figure was created using Biorender.com and partially using Servier Medical Art, provided by Servier, licensed under a Creative Commons Attribution 3.0 unported license.

Table 4
Evolution of feed conversion ratio (FCR) in poultry meat production in the years 1957, 1978, and 2005. Table adapted from Zuidhof et al. (2014). Values are expressed as mean ± SEM. Superscript letters indicate statistically significant differences between time periods (1957, 1978, and 2005).

Animal age (d)	1957	1978	2005	P-value
0-7	2.553 ± 0.258^{a}	1.382 ± 0.030^{b}	1.108 ± 0.026^{c}	<0.0001
0-14	3.300 ± 0.362^{a}	1.506 ± 0.019^{b}	1.275 ± 0.017^{c}	<0.0001
0-21	3.188 ± 0.170^{a}	1.608 ± 0.013^{b}	1.379 ± 0.006^{c}	<0.0001
0-28	3.084 ± 0.093^{a}	1.706 ± 0.019^{b}	1.483 ± 0.008^{c}	<0.0001
0-35	3.003 ± 0.118^{a}	1.832 ± 0.030^{b}	$1.573\pm0\text{-}012^{c}$	<0.0001
0-42	2.882 ± 0.101^{a}	1.899 ± 0.026^{b}	1.674 ± 0.012^{c}	<0.0001
0-49	2.871 ± 0.103^{a}	2.018 ± 0.017^{b}	1.808 ± 0.018^{c}	<0.0001
0-56	2.854 ± 0.096^{a}	2.135 ± 0.037^{b}	1.918 ± 0.015^{c}	<0.0001

In the present study, the FCR was calculated using the data from Aviagen (2022) corresponding to the period between the 35th and 56th day of poultry rearing, as previously described. The FCR was calculated on a daily basis within this range, resulting in an average value of 1.597 ±0.03 (Aviagen, 2022) (Fig. 5). This result is significantly lower than the values reported for 2005 by Zuidhof et al. (2014), showing a further improvement in the feed efficiency of broiler chicken in the last decade. This data confirms the steady progress achieved thanks to the synergy between advanced genetic selection and nutritional optimisation.

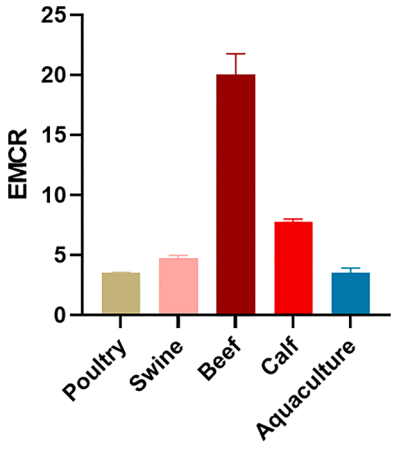

Fig. 5. Comparison of mean Feed Conversion Rate values of main meat producing animals. Values are reported as mean ± SEM.

For pig meat production, we estimated a mean FCR of 2.73±0.14 (Fig. 5) from a synthesis of data from several recent studies, with particular reference to the grower-finisher phase. Studies used include Adam and Butfering (2009); Rabobank Research (2015); Shepon et al. (2016); Pierozan et al. (2016); Gaillard et al. (2020); Heinzl and Caballero (2021) and van der Linden et al. (2025). According to Adam and Butfering (2009), the FCR in growing pigs is around 2.6, a value also confirmed by Heinzl and Caballero (2021). However, as the authors point out, the FCR is the result of a complex interaction between genetic, physiological, nutritional and management factors. The regulation of feed intake and nutrient utilisation is partly determined by gene expression, but is also influenced by sex and physiological status: intact males exhibit higher feed efficiency and increased lean tissue deposition than females and castrated animals, which show slower growth and a greater tendency to accumulate fat. Age and growth phase also have a significant effect on the FCR. In the first weeks of life, piglets grow rapidly and receive diets with high nutrient density giving very low FCRs (1.1-1.2 between 0 and 2 weeks; 1.6-1.8 between 3 and 6 weeks) (Heinzl and Caballero, 2021). With advancing age, however, energy requirements for maintenance increase, while both growth rate and dietary energy concentration decrease, leading to a physiological increase in FCR (Heinzl and Caballero, 2021). Further studies confirm this variability. Gaillard et al. (2020) report values of 2.69, 2.74 and 2.88, differentiated according to rearing system. Pierozan et al. (2016) observe an average FCR of 2.45±0.12, with a range between 2.15 and 2.86, underlining the influence of environmental, genetic and management factors. Higher values were documented by Shepon et al. (2016) (3.1) and Rabobank Research (2015) (3.9), highlighting the potential impact of less efficient production systems. Finally, Van der Linden et al. (2025) analysed the effect of dietary protein content in the grower-finisher period, showing that higher protein content leads to improved feed efficiency. The FCR values recorded were 2.42 for the

low-protein diet, 2.38 for the standard diet and 2.30 for the high-protein diet. These results confirm that diet composition is a strategic factor in the modulation of FCR (Van der Linden et al., 2025).

We have calculated the mean FCR value for cattle to be 8.18±0.69, using data from the main beef breeds (Table 5). This value is highly comparable to the general FCR reported for cattle (8.0), as described by Fry et al. (2018). The variability observed in Table 5 can be attributed not only to genetic differences among breeds, but also to herd management and feeding practices, both of which are key factors in determining overall feed efficiency.

As might be expected, the FCR values calculated for beef cattle are higher than those recorded for calf production, which is characterised by a significantly shorter productive cycle. In Fig. 5, the FCR value for calves was calculated using the data reported of Rajaei-Sharifabadi et al. (2024) for the Holstein breed, which was chosen as a reference precisely because of its shorter production cycle compared to other breeds (Table 3). According to Vavrišínová et al. (2019), the typical production cycles of Holstein calves are 151.8, 198.2 and 203.4 days. Furthermore, as shown by Rajaei-Sharifabadi et al. (2024), the FCR value can vary slightly depending on the energy level of the diet with values of 3.77, 3.55 and 3.88, reported for high, medium and low energy density, respectively. Given the representativeness of these values in calf production systems, we calculated a mean ± SEM FCR value of 3.73±0.10.

As shown in Fig. 5, the mean FCR calculated for the aquaculture sector is 1.45±0.19. This value was obtained from the FCRs of the main fish species previously described. For tilapia, an average FCR of 1.41 ±0.07 was calculated on the basis of data reported in the literature. In particular, Tacon and Metian (2008) and Fry et al. (2018) report an FCR of 1.7, while lower values were observed by Lima et al. (2018), with FCRs of 1.24, 1.30, 1.40 and 1.32, depending on the management practices adopted. Consistent results were also found by David et al. (2021) and Pai et al. (2024), who reported values of 1.2 and 1.44, respectively. This evidence confirms the high efficiency of tilapia in intensive systems and the influence of rearing conditions on feeding performance. Catfish also show good conversion efficiency. According to Kumar et al. (2018), the FCR in these species can range from 2.04 to 2.59, depending on the feeding and management strategy adopted. However, to harmonise the data used in the calculation of an overall mean FCR, the specific value of 1.8 was selected for *S. asotus*, as reported by Ching (2023). At the same time, although the production cycle of Atlantic salmon is generally longer than that of other species, it has a particularly competitive FCR. Collected data indicate an average FCR of 1.15±0.09. In particular, Balseiro et al. (2018) reported values between 1.1 and 1.4, also confirmed by Fry et al. (2018). More recent studies, such as that of Terrey et al. (2024), show that appropriate dietary modulation can further improve conversion efficiency, with reduced FCRs as low as 1.03±0.00 and 0.94±0.02. Finally, although the Atlantic bluefin tuna is the subject of wide interest in cellular agriculture, its FCR has not been included in the mean value shown in Fig. 5. This exclusion is justified by the high FCR observed in conventional farming systems, which is not representative of the aquaculture sector as a whole (see Table 6), but on the contrary highlights the potential of cellular agriculture as an alternative and sustainable approach for this species.

Table 5
FCR of the main beef production (growing and finishing) cattle breeds. Values are reported as mean+SEM.

Breed	FCR	Reference
Aberdeen angus	8.05	Bureš and Bartoň (2018)
Charolaise	9.19±0.27	Unal et al. (2025)
Simmental	12.35±0.28	Unal et al. (2025)
Holstein	7.43	Bureš and Bartoň (2018)
Limousine	5.33	Magrin et al. (2025)
Belgian Blue	6.15±0.18	Keady et al. (2021)
Piemontese	7.1±0.9	Tarantola et al. (2020)
Chianine	9.17	Pauselli et al. (2005)
Wagyu	8.84	Guarnido-Lopez et al. (2024)

Table 6
FCR from bluefin tuna fattening operations around the world. Table adapted from Gamsiz and Gorgout (2022).

Country	Lowest FCR	Highest FCR
Italy	10	17
Cyprus	15	18
Libya	15	15
Malta	14	20
Spain	13	25
Turkey	15	15
Australia	12	15
Mexico	7	12
Mediterranean	10	20

5. EMCR of main livestock systems

To ensure a more accurate comparison with CM, where the final product is potentially entirely edible, the FCR of various livestock species was recalculated by referencing not the live weight, but the actual amount of edible meat obtained. This adjustment enables the calculation of EMCR (Fig. 6), offering a more realistic and comparable assessment across production systems.

For the broiler, according to Aviagen (2022), although the edible meat yield may vary depending on many processing factors (e.g. type of plant, technologies used, manual *vs* automatic boning, cooling, criteria for defining 'edible meat'), the average value of boneless and skinless edible meat yield is around 45% of live weight. This value considers the main commercial cuts (breast, legs, wings) boneless and skinless, intended for human consumption. Consequently, the FCR of 1.597 ± 0.03 must be corrected by dividing by the yield coefficient (45%), yielding an EMCR of approximately 3.55 ± 0.01.

For finishing pigs, data from Cauffman et al. (2020) report that a pig with an average live weight of 113.4 kg provides a warm carcass of about 83.0 kg, corresponding to a yield of 73.2%. Subsequently,

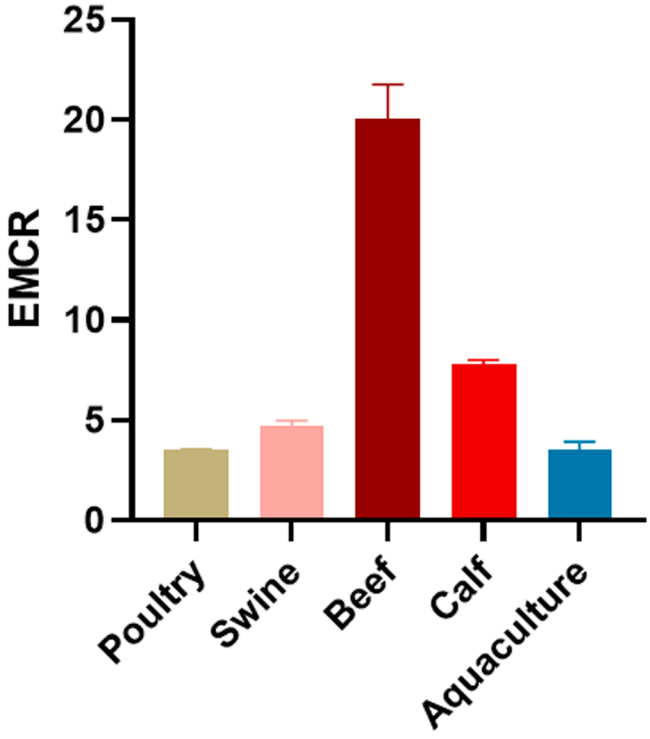

Fig. 6. Comparison of mean Edible Meat Conversion Rate (EMCR) values of main meat producing animals. Values are reported as mean ± SEM.

deboning and trimming result in an edible meat yield of 65.3 kg, equivalent to 57.6% of the live weight. Based on this value, a conventional FCR of 2.73 ± 0.14 results in an EMCR of 4.74 ± 0.24.

For beef cattle, carcass yield and edible meat percentage vary considerably depending on multiple factors, including breed, sex, age at slaughter, feeding regime and husbandry system (Irshad et al., 2013). Considering the variety of breeds included in the analysis and the impossibility of precisely defining the yield for each individual, a standardised average value was adopted, in line with what has been reported in the literature. In particular, according to FAO (2010), carcass yield in beef cattle ranges from 55% to 65% of live weight. These data are also confirmed by Campbell (2020) and Holland et al. (2014), who report a carcass yield of 60% to 64% and 62.5%, respectively. However, the actual edible share of the final live weight differs between the authors: Campbell (2020) reports an edible yield of 38%, while Holland et al. (2014) 44%. These values were used to estimate the EMCR, which ranged from 21.52 ± 1.82 to 18.59 ± 1.57, with a combined mean of 20.06 ± 1.70.

With regard to calves, the values for the Holstein breed were adopted as reference, as described above. One of the main factors influencing edible meat yield is the slaughter weight (Paris et al., 2015). In particular, the authors showed that the edible meat yield in the main cuts (front, sidecut, rear) at different live weights (144.6 kg, 179.7 kg, 227.5 kg and 260.5 kg) is 65.95 kg, 85.88 kg, 108.75 kg and 129.91 kg, respectively. From these values, an edible meat yield of 45.60%, 47.80% and 49.86%, respectively, was derived. Therefore, an average yield value of 47.77% was used to calculate the EMCR in calves. Applying this coefficient to the previously estimated FCR (3.73 ± 0.10), an EMCR of 7.80 ± 0.21 was obtained.

As reported earlier, the average FCR value in the aquaculture sector was 1.45±0.19, calculated from tilapia, catfish and Atlantic salmon. For tilapia, the edible meat yield, intended as boneless fillet, was around 31.32% of live weight, based on an average of five strains (Peterman and Phelps, 2012). Considering an average FCR of 1.41±0.07, this results in an EMCR of 4.50±0.22. However, for *S. asotus*, no specific data on edible meat yield are currently available. Nevertheless, van Riel et al. (2023) report an edible yield between 36% and 50% of live weight for catfish in general, which can be considered as an approximate reference for this species. Based on these data, the EMCR for catfish is between 3.6 and 5.0, with an adopted mean value of 4.3±0.7. Finally, for Atlantic salmon, Talbot et al. (2022) indicate a very high edible flesh yield of 68% of live weight, confirming the production efficiency of this species. An EMCR of 1.69±0.13 is derived from these data. Combining the values obtained for tilapia, catfish and Atlantic salmon gives an average EMCR of 3.50±0.43.

The use of these conversion coefficients, species-specific and based

Table 7
Components and concentrations of ingredients in the culture media for cultured meat. Table modified from Salazar et al. (2016), O'Neill et al. (2021) and Yun et al. (2024).

				Fetal Bovine Serum						
Amino acids (g/L)	Carbohydrates (g/L)	Inorganic salts (g/L)	Vitamins (g/L)	Carbohydrates (g/L)	Growth factors (μg/L)	Inorganic ions (mg/L)	Hormones (mg/L)	Vitamins (μg/L)	Lipids (mg/L)	Nitrogen compounds (mg/L)
Glycine (0.008-0.330)	Glucose (4.5)	Magnesium chloride (0.098-0.2)	Niacinamide (0.001-0.004)	Glucose (0.6-1.0)	βFGF (1-100)	Calcium (160.3-280.6)	Insulin 5.78-577.8	Vitamin A (10-100)	Cholesterol 3.87	Albumin 20000-50000
Lysine (0.000-2.000)		Zinc sulfate (0.0004)	Folic acid (0.001-0.004)	Hexosamine (0.6-1.0)	EGF (1-100)	Chlorides (3.545)		Folate (5-20)	Phospolipids 700-3000	Fetuin 10000-20000
Cysteine (0.024-0.123)		Copper (n.a.)	Ascorbic acid (0.064)	Lactic acid (0.5-2.0)	FGF 1,2,3,4 (1-100)	Iron (0.559-2.793)				Fibronectin 1-10
Serine (0.030-0.557)		Sodium bicarbonate (2.2-3.7)	Pyridoxine (0.001-0.004)	Pyruvic acid (0.002-0.01)	HGF (1-100)	Potassium (195.5-586.5)				Globulins 1000-15000
Alanine (0.009-0.318)		Sodium Phosphate dibasic (0.14-0.141)	Riboflavin (0.0001-0.0004)		GGF 2 (1-100)	Phosphate (189.9-474.9)				Transferrin 2000-4000
Glutamine (0.584)		Calcium chloride (0.2-0.264)	Vitamin B12 (0.0007)		IGF-I (1-100)	Sodium (3100-3570)				Protease inhibitors 500-2500
Glutamic acid (0.011-0.642)		Potassium chloride (0.4)	Choline chloride (0.001-0.004)		IGF-II (1-100)					Urea 170-300
L-Arginine (0.084-1.331)		Ferric sulfate (0.0001)	D-Calcium pantothenate (0.001-0.004)		PDGF (1-100)					
Leucine (0.050-0.560)		Sodium chloride (6.4-6.8)	Thiamine hydrochloride (0.001-0.004)		TGF (1-100)					
Isoleucine (0.050-0.457)					TGF-β1 (1-100).					
Valine (0.020-0.440)										
Aspartic acid (0.013-0.465)										

GF: Growth factors; BFGF: Basic fibroblast growth factor; EGF: Epidermal growth factor, FGF: Fibroblast growth factor; HGF: Hepatocyte growth factor; GGF: Glial growth factor; IGF: Insulin-like growth factor; PDGF: Platelet-derived growth factor; TGF: Transforming growth factor.

on reliable technical and operational sources, is essential to harmonise efficiency metrics between livestock production and CM, providing a more accurate and relevant comparative picture.

6. CMCR of cultured meat

In CM production, the input biomass refers to the nutrients supplied to the cells through the culture medium, while the output biomass represents the amount of edible muscle tissue obtained at the end of the production process. For an accurate estimate of CMCR, it is essential to determine both the number of cells required to produce 1 kg of CM and the concentration of nutrients in the cell growth medium. In the first case, as reported by Hubalek et al. (2022), to obtain 1000 kg of CM, 1×10^{14} cells and a culture medium volume of approximately 20,000 L will be required, assuming a cell density in the bioreactor of 4×10^{7} cells/mL. From the above data, it follows that for 1 kg of CM, 1×10^{11} cells and a volume of 20 L per kg will be required. The second and more complex aspect concerns the identification of the concentration of each component of the culture medium (Table 7). This analysis is crucial to accurately quantify the CMCR.

As previously indicated, this review does not aim to describe the role of individual nutrients, which has already been extensively covered by Yun et al. (2024), but rather to analyse the contribution of each nutrient in determining the FCR of CM. However, this calculation is particularly complex due to the limited data available in the literature.

The amino acid (AA) profile required for CM production was defined based on the study by Yun et al. (2024). The specific quantities of each AA were determined according to the requirements for mammalian cell culture, as reported by Moraes et al. (2008) and Salazar et al. (2016). It is assumed that these values may also be applicable to CM. The values given in Table 7 represent the minimum and maximum requirement of each AAs in the CM process. If the cells require the minimum amount, the total AA consumption is 0.813 g/L. Conversely, if the culture medium is enriched with the maximum amount, the total requirement reaches 7.807 g/L. Consequently, to obtain 1 kg of CM in a 20 L bioreactor, the total amount of AAs required varies between 16.26 g and 156.14 g, depending on the concentration adopted in the culture medium.

At the same time, as described by Furuichi et al. (2021), the most important carbohydrate component is glucose, which is responsible for supplying the cells with energy. Although cell proliferation generally requires high glucose concentrations, excessive levels can reduce the expression of the Pax7 gene, which is crucial for the differentiation of muscle satellite cells (Lagha et al., 2008; Furuichi et al., 2021), and promote the conversion of muscle cells into adipocytes, leading to an accumulation of intracellular lipids (Aguiari et al., 2008; Yue et al., 2010). Contrarily, concentrations that are too low can impair cell growth, regeneration and differentiation of skeletal muscle tissue (Furuichi et al., 2021). To ensure optimal conditions, most culture media are supplemented with glucose at a concentration of 4.5 g/L, which corresponds to a requirement of 90 g glucose to produce 1 kg CM.

As shown in Table 7, minerals are added to the culture medium in the form of inorganic salts. This mode of administration ensures their solubility, stability and bioavailability, enabling them to play an essential role in cell proliferation, differentiation and contraction (Yun et al., 2024). O'Neill et al. (2021) estimated the mineral content in the culture medium for CM production. Considering the sum of the minimum values of each mineral, the total requirement is 9.44 g/L, while the maximum value reaches 11.51 g/L. Applying these figures to the calculation for 1 kg of CM (in 20 L), the required amount of minerals would be 188.77 g and 230.11 g, respectively. However, these calculations do not take into account the minerals present in fetal bovine serum (FBS), subsequently described.

Vitamins play a special role in the context of CM and deserve in-depth analysis. It is crucial to point out that their requirements differ significantly between *in vivo* and *in vitro* conditions, reflecting the different metabolic needs of cultured cells (O'Neill et al., 2021). According to Lamarche et al. (2015), some fat-soluble vitamins are essential for specific cell types in certain contexts, being able to promote myogenesis. However, as reported by O'Neill et al. (2021), it is probable that these vitamins are not strictly necessary for CM production. Water-soluble vitamins, although characterised by limited stability in culture media, are considered essential components in basic animal cell media (Schnellbaecher et al., 2019; O'Neill et al., 2021). Among these, ascorbic acid plays a crucial role in collagen synthesis by fibroblasts, which is crucial for ensuring the structural integrity of cultured muscle tissue. In order to accurately estimate the CMCR, it is necessary to consider the range of vitamin concentrations given in Table 7, with minimum values of 0.071 g/L and maximum values of 0.09 g/L. On a production scale, this translates into a requirement of between 1.4 g and 1.8 g of vitamins per 1 kg of CM in a 20 L bioreactor.

Almost all cell cultures involve the addition of FBS to the culture medium. FBS is a complex mixture (carbohydrates, growth factors (GFs), inorganic ions, hormones, vitamins, lipids and an important source of nitrogen) essential for cell growth (Brunner et al., 2010). Although some companies involved in CM production use FBS to promote cell growth, combining this practice with a strict control and monitoring system (FDA, 2021), its use raises concerns regarding sustainability, safety and ethical implications. Furthermore, it is incompatible with the *animal-free* principle promoted by cellular agriculture (Lanzoni et al., 2022; Lanzoni et al., 2024). For this reason, scientific research is actively exploring sustainable alternatives, with a focus on the valorisation of plant matrices and co-products of the food industry (Mols et al., 2004; Ho et al., 2021; Lanzoni et al., 2022; Sundaram et al., 2025). Although it is plausible that some large companies have already developed viable alternatives, patent coverage limits their disclosure. Consequently, it remains speculative to assess their impact on CMCR. For this, in this review, the values of the main known constituents of FBS (Table 7) will be evaluated to determine the CMCR, taking into account that the exact concentrations, being a derivative of animal origin, are batch-dependent (Lanzoni et al., 2022).

As mentioned above, FBS represents a crucial, albeit variable, source of nutrients and bioactive factors within the culture medium, contributing significantly to cell growth and differentiation processes. Although the carbohydrates present in the FBS are quantitatively lower than those provided by the base medium, there are still significant concentrations of glucose, hexosamines, lactic acid and pyruvic acid, the latter in more modest amounts. These compounds are generally found in the range of 0.6 to 2.0 g/L. Since the inclusion of FBS in cell cultures is commonly between 5% and 20% for mammalian (commonly 10%) and fish cells (Yaffe and Saxel, 1977; Gundry et al., 2009; Lakra et al., 2011), it was decided to standardise the estimates on the basis of an addition of 10% as a representative reference value. Under these conditions, the contribution of FBS to dissolved carbohydrates on a 20 L volume of culture is between 3.40 g and 8.02 g. Growth factors, although difficult to quantify accurately due to high variability between batches, are also a key functional component of FBS. For this analysis, a conservative estimate was adopted, assuming a maximum cumulative concentration of 1 mg/L. In a culture containing 10 % FBS, this is equivalent to a total contribution of approximately 0.002 g per kg of CMCR produced. FBS also contributes a variety of inorganic salts - including calcium, potassium, sodium, phosphates, iron and chlorides - which are added to those already present in the medium, contributing to the electrolyte balance of the culture. Their concentration varies depending on the source of the serum, and the total contribution in a 20 L culture is estimated to be between 7.30 and 9.83 g (values calculated with reference to Table 7).

Among the bioactive components, hormones play a prominent role, with insulin in particular exerting multiple effects: it facilitates glucose uptake, promotes cell proliferation and differentiation, and activates several intracellular signalling pathways (Straus, 1981; Sarabia et al., 1992). Its concentrations in FBS are subject to strong fluctuations between batches, with an estimated intake of between 0.01 and 1.15 g per

kg of CM. Although vitamins are part of the FBS composition, their contribution is negligible. Of greater importance, however, is the lipid fraction, consisting mainly of phospholipids and, to a lesser extent, cholesterol (O'Neill et al., 2021; Yun et al., 2024). These lipids play an important role in muscle maturation by influencing the expression of specific proteins and enhancing glucose uptake by cells (Yun et al., 2024). Phospholipid concentrations are estimated between 0.7 and 3.0 g/L, corresponding to an overall intake of 1.4-6.0 g per 20 L culture.

Finally, FBS is characterised by a rich content of nitrogen compounds with high biological functionality, including albumin, fetuin, fibronectin, globulins, transferrin, as well as urea and protease inhibitors. Again, the variability between batches is marked, with contributions ranging from 7.34 to 183.62 g per kg of CM produced.

In light of the reported data, it was possible to calculate the CMCR, considering two conditions: the use of the minimum and maximum concentrations of each component of the culture medium, as described and illustrated in Fig. 7.

The obtained CMCR values range from 0.316 to 0.687, but we consider it unlikely that the lowest concentrations would provide adequate support for the metabolic and proliferative needs of the cells. The maximum estimated CMCR value is similar to the FCR reported by Hubalek et al. (2022) and the Good Food Institute (2021), which indicate an FCR of 0.8. Particularly interesting are the data presented by Good Food Institute (2021), which calculated this value assuming that 75% of the AAs in the culture medium are derived from soy hydrolysate and 25% from conventional (microbial and chemical) sources, but without taking into account the differences in water consumption associated with ingredient production. The ingredients of the medium include glucose derived from biomass, with co-products such as soybean meal and corn solubles. The process also involves the use of organic chemicals, mainly methanol, and inorganic compounds such as acids, ammonium carbonate and ammonia. It is important to note that this is a preliminary estimation. For a more accurate and reliable calculation of the CMCR, all inputs and outputs - including resource consumption and co-product generation - must be fully and accurately accounted for. Certainly, cell agriculture for the production of cell-based products aims to investigate the ingredients of the culture medium in line with the principles of sustainability, whose potential has been extensively discussed by Grossmann (2024).

As pointed out by the Good Food Institute (2021), commonly used FCR values for CM are < 1 because they do not take into account the water content in the inputs and outputs of the production process. To overcome this limitation, we normalised the most representative FCR value for realistic conditions (0.687) based on the dry matter (DM) content of 1 kg of CM, i.e. 30% by weight, as estimated by the Good Food Institute (2021). Considering a total DM input of 686.18 g (Fig. 7), the Apparent Cell Conversion Yield (ACCY) is 43.7% (300 g DM output / 686.18 g DM input) (Fig. 8). Consequently, correcting the CMCR to take into account DM only, we obtain a value of approximately 2.29 (CMCR on DM), i.e. the ratio of input to output expressed in terms of DM (Fig. 8).

Despite the correction for DM content, the CMCR DM value is still highly efficient when compared to the EMCR of livestock, as shown in Fig. 9.

Although useful, the proposed calculation should be considered purely theoretical and used only as a preliminary tool for estimating the FCR of alternative culture media used in CM. For a realistic assessment, it is necessary to take into account numerous variables. In practice, the consumption of culture medium can vary significantly depending on several critical parameters. Among these, one of the most relevant is the cell type used: cells with different origins and differentiation potential (such as myoblasts, mesenchymal stem cells or induced pluripotent stem cells) have different nutritional requirements, proliferation rates and expansion times, directly influencing the amount and composition of the medium required (Chen et al., 2022). A further determining factor is the degree of complexity of the final product (Ahmad et al., 2018; Romao et al., 2023): the production of simple, loosely structured muscle tissue intended for minced or similar products generally requires shorter and less intensive culture cycles than the generation of mature, organised tissues that mimic the structural and functional properties of conventional meat. In the latter case, in addition to cell proliferation, it is necessary to promote differentiation, myogenic fusion, the formation of three-dimensional structures and sometimes even vascularisation or innervation of the construct (Siddiqui et al., 2022; Lanzoni et al., 2022). All these processes lead to longer culture times and increased complexity in the management of the medium, both in terms of quantity and quality.

In parallel, a 10% inclusion of FBS was assumed, but this percentage can vary considerably, from a minimum of 5% to a maximum of 20%, depending on the cell type and culture protocol (Yaffe and Saxel, 1977; Gundry et al., 2009; Lakra et al., 2011). Increasing the percentage of FBS leads to a proportional increase in the calculated FCR. It is desirable, however, that in the near future, CM companies adopt *animal-free* media, thus making it necessary to recalculate the CMCR based on the chemical and nutritional composition of the alternative ingredients used (Mols et al., 2004; Ho et al., 2021; Lanzoni et al., 2022; Sundaram et al., 2025). In this context, it will be crucial to assess the bioavailability and actual assimilability of these nutrients by cultured muscle cells. A further critical parameter to be incorporated into the calculation of the CMCR is the correct cellular metabolic efficiency, i.e. the ratio of absorbed nutrients to actually synthesised biomass. In the simplified model currently adopted, we have calculated a 43.7 %. It is difficult to confirm these data due to a lack of literature on the conversion efficiency of cultured cells in bioreactors (Humbird, 2021). It is well known that cell metabolism inevitably results in the formation of waste by-products, such as ammonia and lactate, which not only represent a loss in terms of nutrient utilisation, but also exert a cytotoxic effect, impairing cell proliferation and viability at advanced stages of culture (Hubalek et al., 2022; Yun et al., 2024). These secondary metabolites are thus directly responsible for an increase in CMCR, as they limit the final biomass yield. Metabolic bioengineering has been indicated as a promising strategy to increase the efficiency of cellular metabolism (Nielsen and Keasling, 2016), by optimising metabolic pathways, introducing alternative biosynthetic pathways and suppressing catabolic circuits responsible for waste formation. In parallel, recent approaches (Hubalek et al., 2022) have demonstrated the efficacy of formulating optimised growth media to minimise the accumulation of products of catabolism,

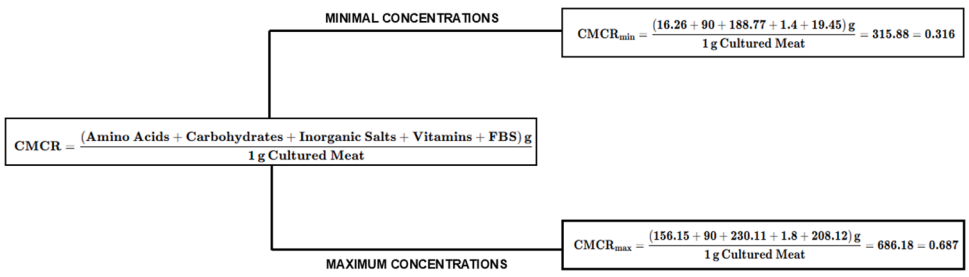

Fig. 7. Minimum and Maximum Cultured Meat Conversion rates (CMCRs).

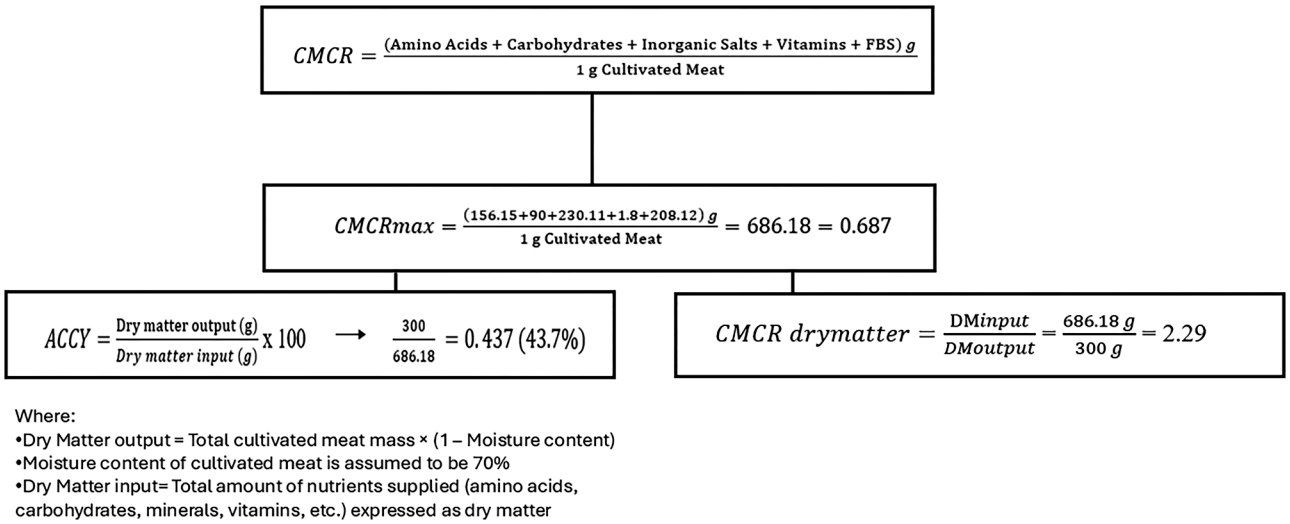

Fig. 8. Calculation of Apparent Cell Conversion Yield (ACCY) and Cultured Meat Conversion Rate (CMCR) based on the dry matter content of cultured meat.

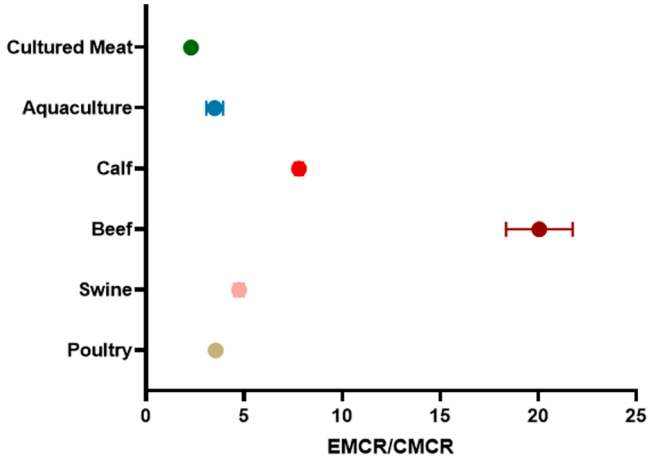

Fig. 9. Theoretical CMCR (Cultured Meat Conversion Rate) calculated on dry matter content of cultured meat compared with EMCR (Edible Meat Conversion Rate) of animal production. Values are reported as mean ± SEM.

improving cell yield in the context of CM. Therefore, an accurate and applicable calculation of CMCR in the cellular context will necessarily have to integrate information on the specific metabolism of the cell type used, the composition of the culture medium, the conversion efficiency in bioreactor systems, and the management of metabolic waste. Only through an integrated and experimentally validated evaluation will it be possible to realistically estimate the FCR of alternative cellular protein production systems. However, it is important to emphasise that the CMCR calculation is not intended to denigrate or diminish the important contribution that the livestock sector makes in animal protein production. On the contrary, the aim is to assess and improve the efficiency of alternative protein production systems, creating complementary opportunities that can contribute to a more sustainable and diversified future in the global food landscape, without compromising the resources and benefits historically provided by the sector.

7. Conclusion

The theoretical and hypothetical model proposed to calculate the FCR of CM (CMCR) suggests a high potential efficiency of the system, with estimated values lower than those observed in conventional livestock sectors. This indicates that CM could represent a competitive alternative in terms of nutritional conversion. However, it is important to interpret these values with caution. The calculation is based on theoretical conditions. Furthermore, the addition of 10% FBS was considered, a condition that does not reflect the animal-free formulations towards which the cellular agriculture sector is moving. Despite the limitations of the model, this study represents a significant initial step in the definition of CMCR. It provides a useful framework for the development of more accurate and experimental metrics, which will need to include actual metabolic efficiency, cellular by-product management and the use of alternative, sustainable and standardised culture media. Such tools will also be essential to comprehensively assess the environmental impact of cellular versus conventional animal systems, considering factors such as energy use, greenhouse gas emissions, land and water footprints. Additionally, future research should incorporate comparisons of the nutritional and health characteristics of cultured and conventional meat, to ensure that improvements in production efficiency are aligned with nutritional quality and consumer health outcomes. These efforts will be crucial for objective comparisons between the performance of innovative and traditional food systems, and to steer the industry towards scalable and sustainable solutions.

Ethics approval

Not applicable.

Data and model availability statement

Not applicable.

Consent form

This study did not require the approval of an ethics committee or informed consent, as no human subjects or traceable data were involved.

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CRediT authorship contribution statement

D. Lanzoni: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Conceptualization. **I. Givens:** Writing – review & editing, Writing – original draft. **C. Giromini:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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