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An Empirical Study on Italy's Competitiveness in the Cell-Based Meat Market

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INTRODUCTION

According to the latest United Nations projections, the world population will reach 8.5 billion in 2030 and nearly 10 billion in 2050. The middle class now accounts for half of the world's population and is expected to expand beyond 5 billion by 2030. In light of this, as living standards rise, consumption and demand for resource-intensive goods will also increase. By 2030, global demand is expected to increase by 35 percent for food, 40 percent for water, and 50 percent for energy. To ensure that this beneficial increase in living standards does not put disproportionate pressure on the planet's carrying capacity and available resources, we need to take full advantage of green technologies and processes that are already relatively mature and support the development of other technologies, still in the experimental stage, that can make human activities net zero emissions. Although animal products contribute around 18% of calories and 37% of protein to the average global diet, the impacts on the environment are disproportionately large compared to non-animal products in diets. Without interventions food system emissions alone could preclude Paris Agreement climate targets to limit warming at 1.5 °C by 2050. Given that animal meat consumption is projected to rise by more than 70% by the year 2050, compared to 2010 (FAO 2011), cellular agriculture technologies that can ultimately reduce the amount of animal agriculture are of paramount importance, as any improvements to conventional animal agriculture may be offset by anticipated growth. In light of this, this thesis aims to conduct an empirical study of Italy's competitiveness in the cellular meat market. The quantitative and qualitative information needed to carry out the empirical study was obtained through primary data by conducting interviews with business representatives and professionals conducting research and commercial implementation in the field of cellular agriculture. The research not only analyzes the economic aspects, which are those of greatest interest for the purposes of the research objectives, but also provides a description of the regulatory framework, which influences the choices and expectations of investors and entrepreneurs.

1 The Context

The meat industry stands as a cornerstone of the global food system, providing nourishment, economic value, and livelihoods to billions across the world. The value of the meat industry is underscored by its substantial contribution to economies through production, processing, distribution, and trade, creating a complex network that supports both local communities and international markets. However, these benefits come hand in hand with environmental considerations, as the meat industry's resource-intensive supply chain and greenhouse gas emissions have sparked debates about its environmental impact. This section examines the interplay between the market value, efficiency, and negative externalities of the meat industry, aiming to understand its role in a world striving for balance between human physiological needs and ecological preservation.

1.1 The Global Meat Industry and its Market Value

As a major driver of agricultural production, trade, and employment, the meat industry contributes significantly to GDPs worldwide. Beyond its economic impact, meat also holds cultural and nutritional significance, reflecting diverse culinary traditions and providing a rich source of essential nutrients. The traditional meat industry involves the companies engaged in livestock agriculture for the production and distribution of meat and meat products. In economics, this industry is a fusion of primary and secondary activities and, therefore, hard to characterize strictly in terms of either one alone. In most countries, the meat supply chain is heavily vertically integrated, which has allowed this industry to become highly efficient in every aspect of the production and processing of livestock. The largest part of the meat industry is the meat packing industry, which handles the slaughtering, processing, packaging, and distribution of meat from livestock. The global meat market reached a value of $1.4 trillion in 2022. Based on total sales value, the ten largest companies globally are JBS, Tyson Foods, Cargill, BRF, Vion, Nippon Meat Packers, Smithfield Foods, Marfrig, Danish Crown Amba, and Hormel Foods.

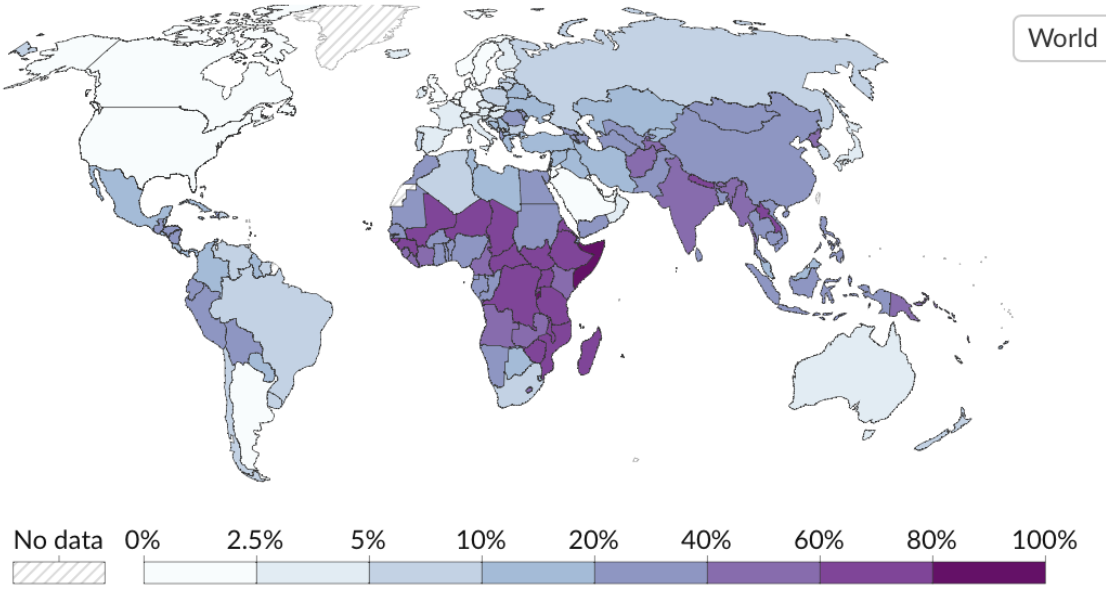


Figure 1.1 Share of the labor force employed in agriculture, World, 2019

In many low- to middle-income countries, the majority of the labor force work in agriculture and rely on it as their primary source of income.

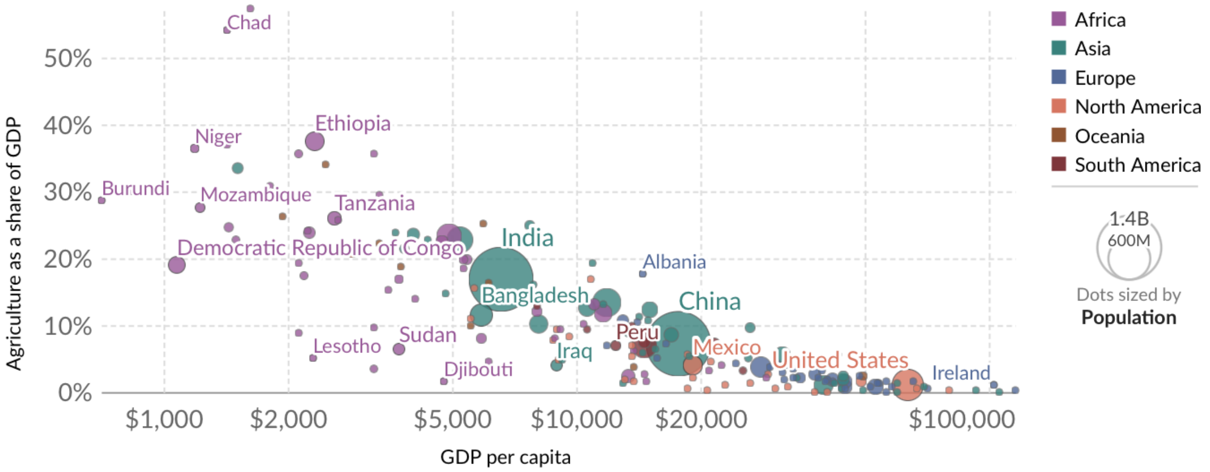


Figure 1.2 Agriculture as a share of GDP vs. GDP per capita, 2021

As countries get richer, the share of the population employed in agriculture decreases since most people move towards employment in industry and services. In advanced and emerging economies, the share of GDP from agriculture rarely exceeds 15 percent.

1.1.1 Production

Over the past 50 years, global meat production has increased more than fourfold. In 2021, global meat production amounted to 352 million tons. Regionally, Asia is the largest meat producer, which accounts for around 40 percent of total meat production.

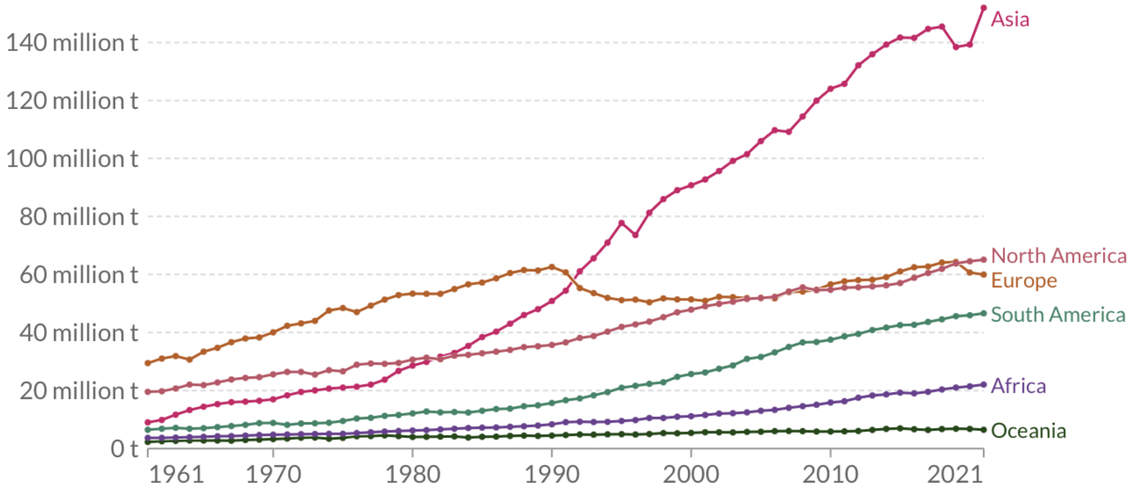


Figure 1.3 Global meat production, 1961 to 2021

This regional distribution has changed significantly in recent decades. In 1961, Europe and North America were the leading meat producers, with 42% and 25%, respectively, and Asia accounted for only 12%. By 2021, Europe and North America's shares have fallen to 17% and 18%, respectively. This reduction in production share was despite a large increase in production in absolute terms: Europe's meat output has approximately doubled over this period, while North American output has increased 2.5-fold. In Asia, however, meat production has increased 15-fold since 1961. Other regions have also experienced significant absolute increases in production, with output in all regions growing more than 5-fold over this period.

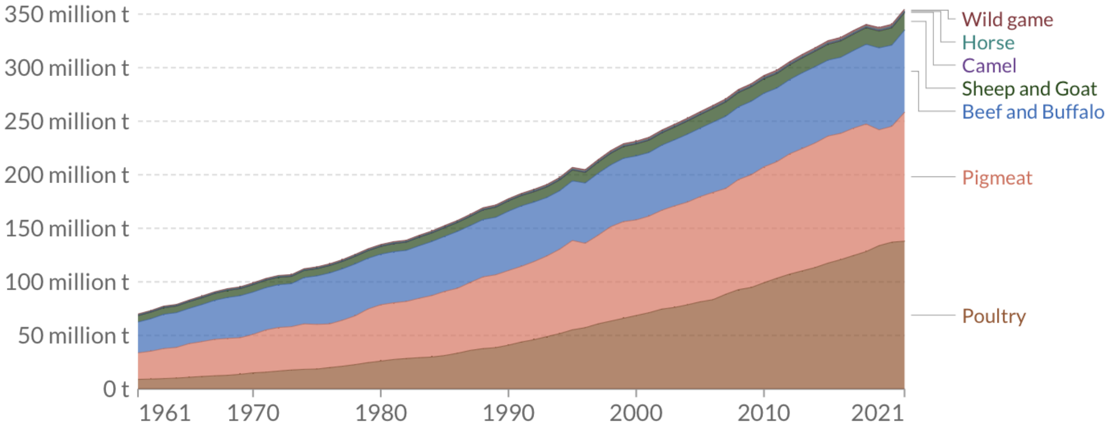


Figure 1.4 Global meat production by livestock type, 1961 to 2021

Globally, the dominant livestock types are poultry, pig meat, and cattle. However, the distribution of meat types varies significantly across the world; in some countries, other meat types account for a considerable share of total output. Although production of all major meat types have been increasing in absolute terms, the share of meat types has changed substantially in relative terms.

1.1.2 Consumption patterns

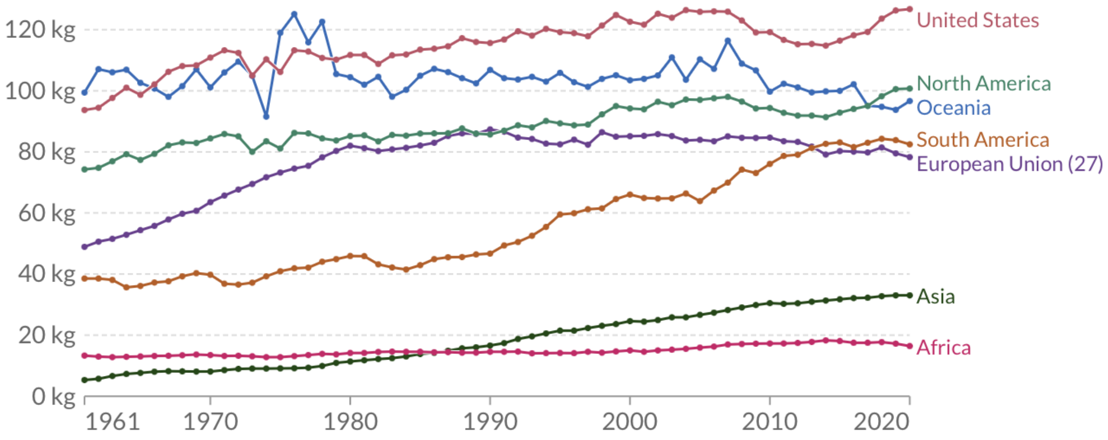


Figure 1.5 Meat supply per person, World, 1961 to 2020

As a global average, per capita meat consumption has increased roughly 20 kilograms since 1961. The direction and rate of change across countries is highly variable. Growth in per capita meat consumption has been most significant in countries that have experienced a strong economic development. The major exception to this pattern has been India, where per capita meat consumption in 2013 was almost the same as in 1961 at less than 4 kilograms per person. Being a cheap and efficient source of protein, poultry stands out as the most popular meat by weight consumption in 70 countries, or about 40% of all countries. While the United States and China eat the most chicken by absolute numbers, the countries rank 7th and 112th respectively when it comes to poultry consumption on a per capita basis. Several island nations - St. Vincent and the Grenadines, Trinidad & Tobago, Samoa – along with Israel eat more than 60 kilograms of poultry meat per person on an annual basis. Regionally, poultry consumption is widespread in almost all of the Americas, the United Kingdom, Australia, South Africa, as well as the Middle East.

Hong Kong leads the world in yearly pig meat consumption per capita at 55 kg. Poland and Spain, who are also top pork producers, rank close behind Hong Kong with similar consumption numbers. Indeed, pork is the most consumed meat in many European countries with local histories of pig meat foods, as well as in a few countries in Africa and one Southeast Asian country.

Argentina is the world leader in bovine meat consumption, as its population eats nearly 47 kg of bovine meat per person a year. Many South American countries have a rich culinary history with beef. In addition to South America, beef consumption data highlight a number of Central Asian and East African countries.

Meat consumption is highest across high-income countries, where, however, changes in consumption have been much slower, with most stagnating or even decreasing between 1961 and 2020. Consumption trends across Africa vary greatly: some countries consume as low as 10 kilograms per person a year while higher-income nations consume between 60-70 kilograms per person.

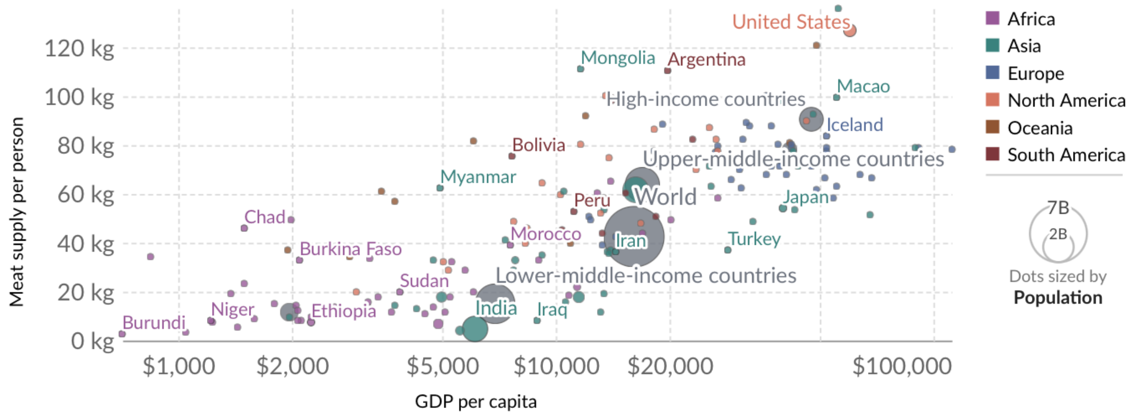


Figure 1.6 Meat consumption vs. GDP per capita, 2020

When making cross-country comparisons, one of the strongest determinants of how much meat people eat is their income. As shown in figure 1.5, there is a strong positive relationship between per capita meat supply and average GDP per capita: the richer a country is, the more meat the average person typically eats. Meat demand is associated with higher incomes and a shift to food consumption changes that favor increased proteins from animal sources in diets.

1.1.3 Livestock productivity

Productivity rates, measured in kilograms per animal, vary considerably between and within countries.

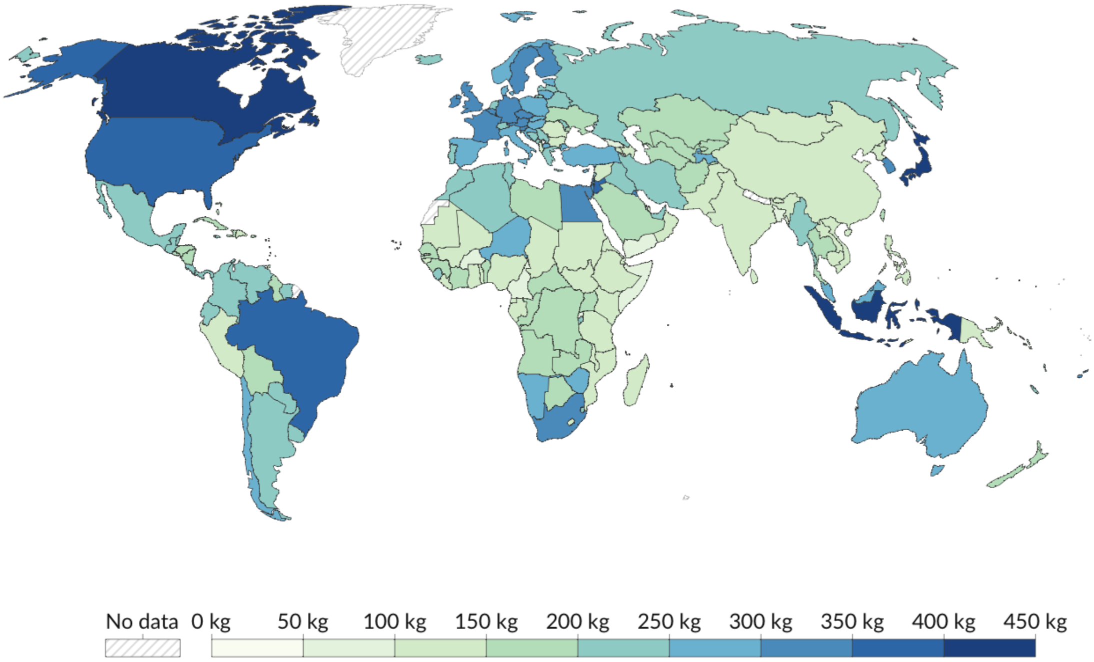


Figure 1.7 Cattle meat per animal, World, 2021

As for cattle meat, North America is the continent with the highest productivity. Europe and South America's productivity lies at the same level, although European variability is lower than in South American countries. Oceania ranks fourth. The relatively low productivity of Africa and Asia depends both on the lower yield per animal and the greater variability of productivity (Figure 2.7).

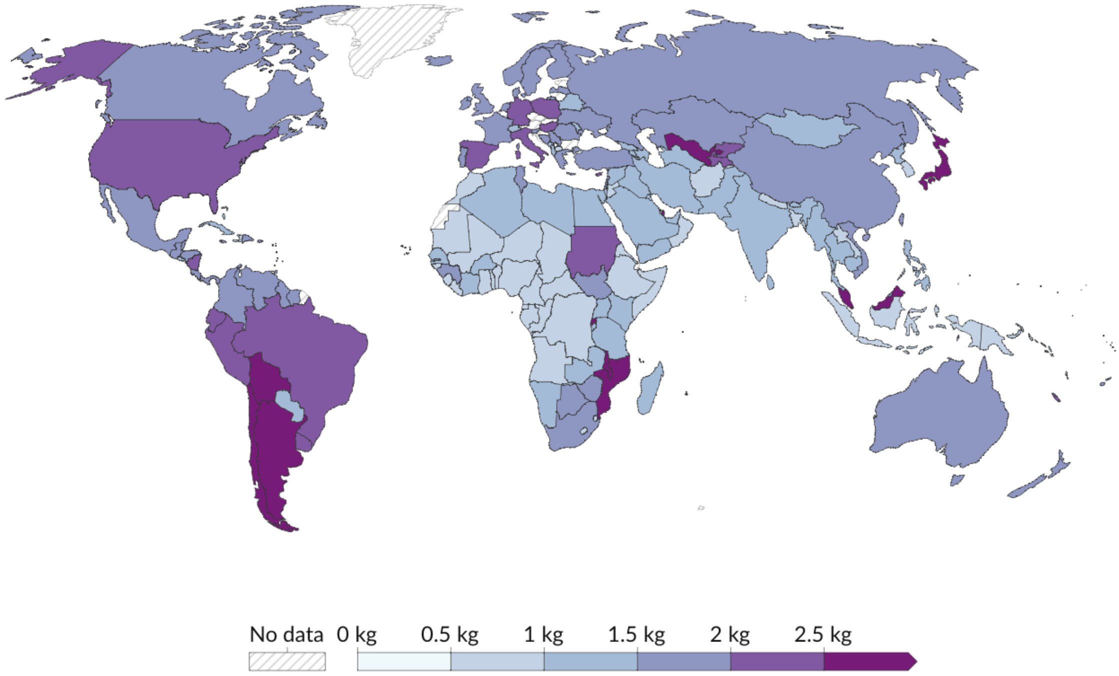


Figure 1.8 Poultry meat per animal, World, 2021

North America and South America, which produce 2.35 kg of poultry meat per animal, have the highest average productivity.

The average productivity in Europe is almost 2 kg per animal.

Asia and Africa hold the last positions, with average productivity at around 1.4 kg per animal.

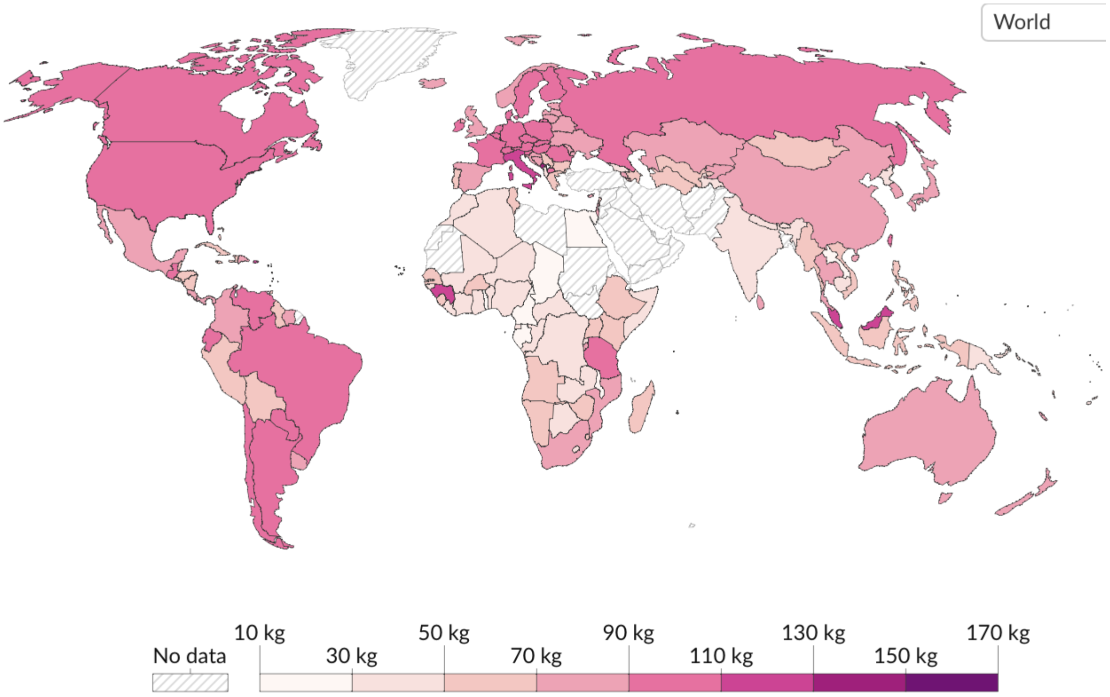


Figure 1.9 Pig meat per animal, World, 2020

As for pig meat, North America and Europe have the highest productivity, at around 100 kg per animal. South America and Asia also have relatively high productivity, around 84 kg per animal. Malaysia, China, Japan, and Thailand are the largest contributors in Asia while Ecuador, Venezuela, Chile, and Paraguay have the highest yields in South America.

With 52 kg per animal, Africa has the lowest productivity.

1.1.4 Italian Meat Industry

The agricultural sector currently accounts for roughly 2 percent of the national value added in Italy. More than 850,000 people are employed in the “Crop and animal production, hunting and related service activities” sector (*FAOSTAT, 2021*). Self-employed workers represent almost half of the total workforce in agriculture (*FAOSTAT 2021; Italian Agriculture In Figures, CREA, 202*2).

Gruppo Veronesi, Gruppo Amadori, Fileni and Martini Alimentare have the largest market shares and have become heavily vertically integrated companies. However, the Italian meat industry also boasts a multitude of smaller, artisanal producers, particularly in the cured meat sector.

Italy is the fifth largest meat producer in Europe, following Spain, Germany, France and Poland. Over the last 50 years, Italian meat production has more than doubled, increasing from 1.47 million tons per year to 3.7 million tons, which accounts for about 1 percent of the world's production and 6 percent of the amount produced in the European Union.

Different regions specialize in the production of specific meats due to their unique climates, traditions, and geographical conditions. Italy is known for its pork products, especially cured meats, and for many high-quality beef breeds. Chicken and turkey are the primary poultry meats produced. Lamb and goat meat are consumed especially in the southern regions and during specific festive periods such as Easter.

Italy produces around 800,000 tons of beef and 1.4 tons of both pork and poultry each year, accounting for 7.5 percent, 4.5 percent and 6.4 percent of total European production, respectively. In 2021, crop production was worth 32 million, an increase of 5.7 percent over the previous year. Especially in rural areas and specific regions, traditional methods of raising livestock still prevail. This can include free-range farming and organic practices. However, with the demand for meat, there has also been a rise in more industrialized methods of meat production in certain parts of the country.

Italy is a net exporter of poultry and a net importer of pork and beef. In 2021, Italy exported $446 million and imported $209 million in poultry meat. The main destination of poultry exports are Germany ($181M), Greece ($32M), France ($29M), United Kingdom ($26M), and Austria ($25M). On the other hand, Italy imports poultry meat primarily from Germany ($68M), Netherlands ($33M), Poland ($25M), Greece ($22M), and Hungary ($15M). In 2021, Italy exported $264 million and imported $2.07 billion in pig meat. The main destination of pig meat exports are China ($82M), Japan ($41M), Romania ($14M), Spain ($12M), and France ($11M). Italy imports pig meat primarily from Germany ($758M), Netherlands ($322M), Spain ($303M), Denmark ($265M), and France ($160M). In 2021, Italy exported $524 million and imported $1.97 billion in bovine meat. The main destination of bovine meat exports are Germany ($86M), Netherlands ($84M), Greece ($82M), France ($57M), and Bosnia and Herzegovina ($50M). Italy imports bovine meat primarily from Netherlands ($359M), Poland ($358M), France ($351M), Spain ($208M), and Ireland ($191M) (Observatory of Economic Complexity).

On average, pig meat is consumed the most, followed by poultry and beef. An Italian consumes about 100 kg of meat per year, of which 33 kg is pork, 20 kg poultry and 16 kg beef. Over the last 10 years, meat consumption has decreased by 21%, from 90 kg per capita per year to 71 kg. Italians eat much less pork (-21%) and beef (-29%). Poultry consumption, on the other hand, increased by 12%, reaching more than 500 million units. The evaluation by International Agency for Research on Cancer on the carcinogenicity of red meat and processed meat consumption in 2015 is believed to have had a negative effect on its consumption. Another reason has been the growing sensitivity to the alleged or actual cruel conditions of cattle and pig farming. It seems, however, that this has not been the case for chickens. Many also attribute the sharp drop in rabbit and horse consumption, by 30 and 70 percent, respectively, to the same concerns about animal welfare. Beyond health and emotional reasons, no doubt reduced purchasing power was another reason behind the shift from red meat to white meat. Due to its higher production costs, beef is more expensive than poultry and pork. As is often the case, when disposable income or purchasing power decreases, people tend to buy less beef, favoring poultry and pork. Additionally, there is a growing trend among consumers, especially the younger generation, for sustainably raised meat.

1.2 Feed-to-Food Conversion Efficiency

Conversion ratios serve as critical metrics for understanding actual production efficiency and coming up with ideas to improve it. These ratios not only hold economic significance for producers but also influence the environmental impacts of the consumed meat, due to the higher input demand caused by a lower animal feed conversion efficiency. For example, feed accounts for about 70% of the overall cost in the poultry industry (Willems et al. 2013), and, thus, improving feed efficiency is a key objective in poultry production. Genetic and breeding approaches has proven effective in improving feed efficiency. In particular, feed utilization of commercial broilers has been dramatically improved over the last several decades through the artificial selection of feed efficiency traits (Siegel 2014; Zuidhof et al. 2014; Tallentire et al. 2016), which include the feed conversion ratio (FCR) and the residual feed intake (RFI). Feed efficiency (FE), which is the output divided by the input, is also used.

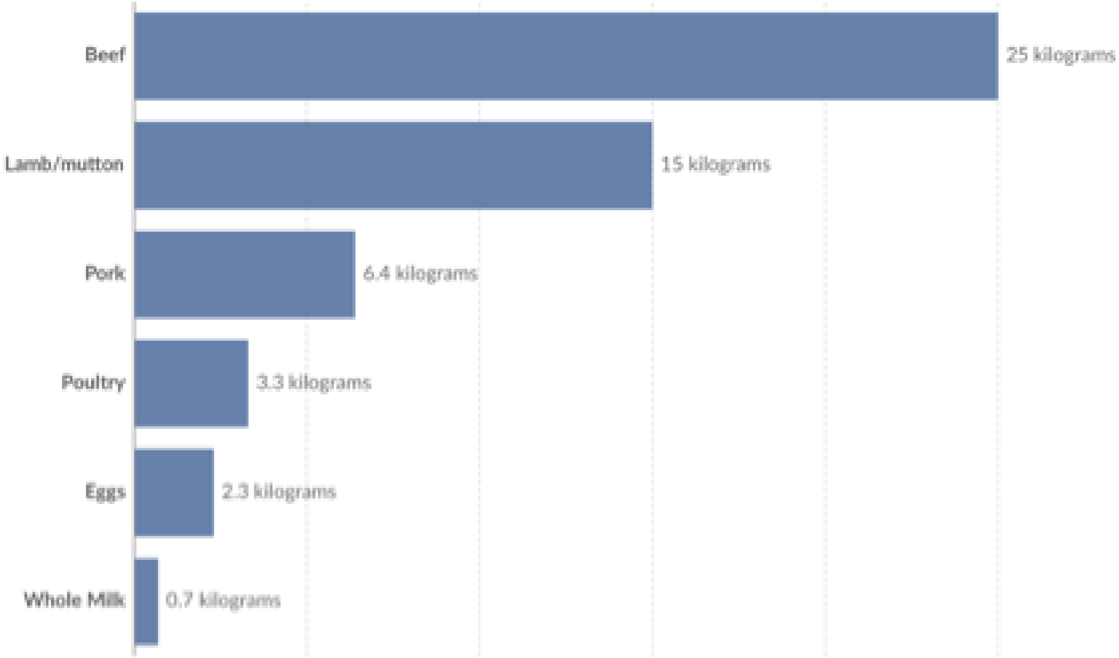


Figure 1.10 Feed required to produce 1 kg of meat or dairy

The choice of conversion ratios depends on many parameters and the farmers' expected output. For example, FCR is an inappropriate indicator for selecting animals to improve genetics because it results in larger animals that cost more to feed. Therefore, RFI is used, which takes into account the animal's body weight, weight gain, and composition (Dan W. Shike, 2013). Despite the many methods of quantifying production efficiency previously mentioned, FCR, protein conversion efficiency and energy (caloric) conversion efficiency are used in this paper in order to show the relatively poor efficiency of modern meat processing.

The feed conversion ratio shows the quantity of feed inputs required to produce one kilogram of edible product, and is measured in kilograms of dry matter feed per kilogram of edible weight product. Lower FCR values indicate higher efficiency. A chicken, for example, needs around 2.3 kilograms of feed to gain 1 kg of weight. A pig eats 6 kilograms of feed to gain one kg of weight. Beef is by far the least efficient: 25 kilograms of feed to gain 1 kg of weight. FCR is a function of the animal's genetics and age, the quality and ingredients of the feed, the conditions in which the animal is kept, and storage and use of the feed by the farmers. Indeed, livestock that is raised in North America and Europe is more likely to converts feed into meat more efficiently. RFI, on the other hand, is defined as the difference between the true and predicted feed consumption based on multiple linear regression equations of the requirements for production and body weight maintenance over a specific period.

The protein conversion efficiency of meat production measures the percentage of protein inputs as feed effectively converted into animal product. Beef has the lowest protein efficiency:

only 4% of beef's protein feed input is converted into edible product, and the remaining 95% is lost during conversion. Pigs and chickens have a protein efficiency ratio of 8.5% and 20%, respectively.

The same rationale is true for the energy efficiency of meat production, which is measured as the percentage of energy (caloric) inputs as feed effectively converted to animal product. The energy conversion efficiency of beef is even lower than its protein efficiency, as only about 2% of the caloric feed input is converted to edible output. The energy efficiency of pork is the same as its protein efficiency (8.5%). The energy conversion efficiency of poultry is almost 15%.

1.3 Environmental Impact of the Meat Industry in the 2030 Agenda

Thanks to the numerous increases in labor productivity, yields, and daily macronutrient supply, fostered by the Third and Fourth Industrial Revolutions, the food system has lifted millions of people out of undernourishment. However, given its substantial and wide-ranging environmental implications, the meat industry is considered a major obstacle to achieving the Sustainable Development Goals (SDGs) outlined in the United Nations' 2030 Agenda.

SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth): the traditional meat industry is a significant source of employment and income for millions of people globally, including many smallholder farmers and others working along the supply chain, contributing to poverty reduction and economic growth.

SDG 2 (Zero Hunger): livestock farming is a crucial source of nutrition, providing essential nutrients for human health and promoting food security in many regions. As with the development and adoption of many other technologies, the transition to a net-zero emissions meat industry involves several trade-offs.

SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action): The traditional meat supply chain has a substantial environmental footprint, including high water and land use, and is a significant contributor to greenhouse gas emissions.

SDG 14 (Life Below Water) and SDG 15 (Life on Land): Conventional meat production often leads to tropical and subtropical deforestation, biodiversity loss, and water pollution, impacting both terrestrial and aquatic ecosystems.

SDG 3 (Good Health and Well-being): Overconsumption of red and processed meat and associated dietary patterns have been linked to increased risks of certain health conditions, leading to calls for more moderate and balanced consumption.

SDG 6 (Clean Water and Sanitation): water-intensive, traditional meat industry contributes to water pollution through runoff of nutrients, antibiotics, and other contaminants, impacting water quality and aquatic life.

The latest projections by the United Nations suggest that the world's population could grow to around 8.5 billion in 2030 and 9.7 billion in 2050 (World Population Prospects 2022). Half the world's population is now considered middle class and is expected to expand to 5.3 billion by 2030. As living standards rise, so will consumption and demand for resource-intensive goods, based on current trends. By 2030, global demand is expected to increase 35% for food, 40% for water, and 50% for energy. This section explores the environmental impact of the global traditional meat supply chain and the challenges confronting innovators. The last part deals with the environmental impact of the meat supply chain in Italy.

1.3.1 Carbon footprint

Each year the world adds 51 billion tons of greenhouse gases, measured in CO2e, to the atmosphere. Even though this figure may go up or down a bit from year to year, it is generally increasing.

There are a wide range of estimates for how much of the world's total greenhouse gas emissions come from the food system. The IPCC Special Report on Climate Change and Land reports a range of 10.8 - 19.1 billion tons of carbon dioxide emissions per year, which is between 21% and 37% of global total emissions. In light of this, the estimates from Poore and Nemecek' (2018) and Crippa et al. (2021) fall in the middle of this range. Although they use different methods to come up with these numbers, the estimates are close to each other.

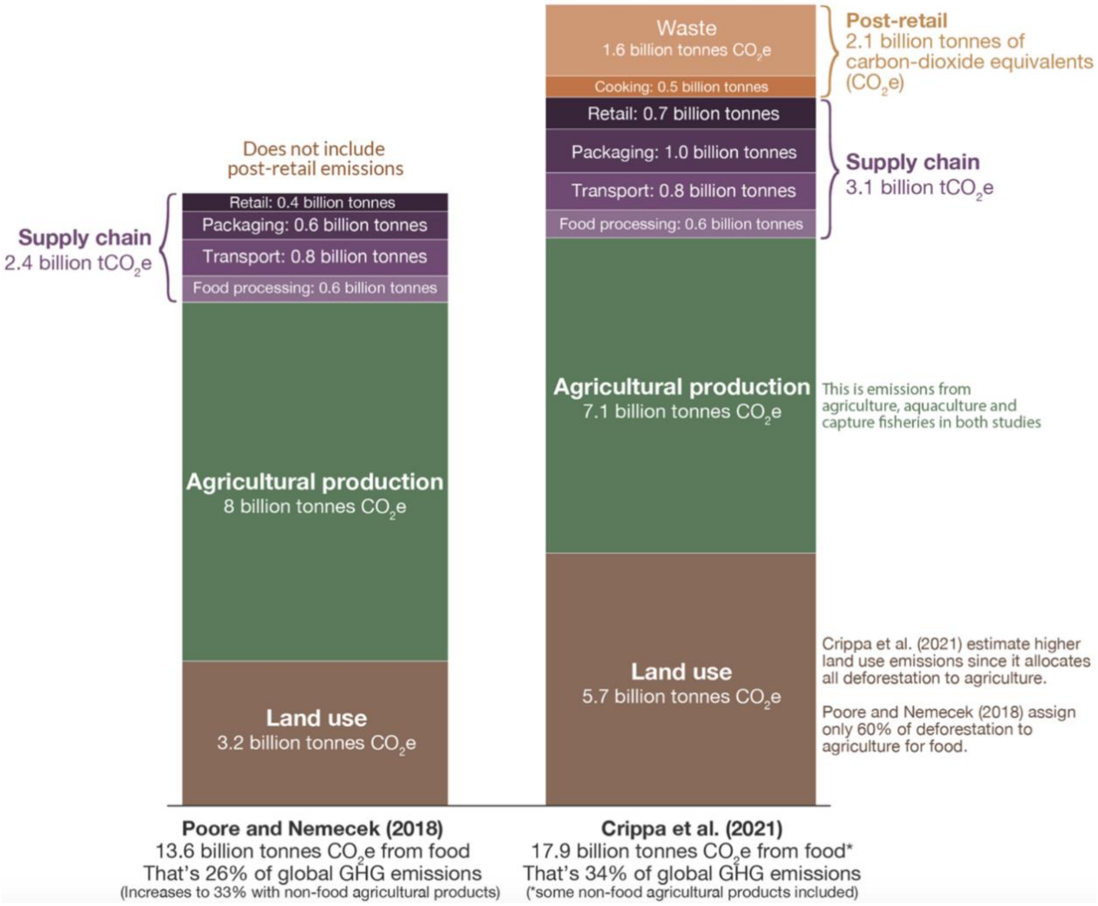


Figure 1.11 Global GHG emissions of the food system, Poore and Nemecek (2018), Crippa et al. (2021)

While Poore and Nemecek only quantify emissions up to the retail stage of the value chain, Crippa and colleagues have figured out a more comprehensive measurement of GHG emissions (scope 1, 2, 3), considering even energy use by consumers and consumer waste. The biggest difference is in land use emissions. This can be largely explained by differences in the attribution of deforestation. Crippa et al. allocate all of global deforestation to agriculture but only around 80% of deforestation is driven by agricultural expansion. Poore and Nemecek only allocated 60% of deforestation to food systems. Land use emissions due to agriculture are likely to be somewhere in the middle of these two values. The other main difference is that Poore and Nemecek only include food products, while Crippa et al. also include wool, leather, rubber, textiles and some biofuels. Raising animals for food is the highest contributor in the "agriculture, forestry, and other land use" sector, which involves various greenhouse gases.

Global animal agriculture accounts for 16.5-19.4% of total greenhouse gas emissions and is by far the largest contributor within food system emissions, twice as much as plant-based sources (Crippa et al. 2021; Twine 2021; Xu et al. 2021). Enteric fermentation alone contributes 27 percent to global methane emissions (Global Methane Initiative 2015; Grossi et al. 2019).

Within agriculture, CO_2 plays a marginal role when compared to CH_4 and N_2O that account for 85% of all the greenhouse gases in this agriculture, forestry, land use sector. Additionally, animal agriculture is responsible for about one-third of all nitrogen emissions. Of these, 68% come from feed production.

When carrying out carbon footprint accountings, there are also large differences in emissions of the same foods depending on the farming system, the origin of calves (dairy-based or suckler-based), the production method (organic or non-organic) and the diet (concentrate-based or roughage-based). For example, producing 100 grams of protein from beef ranges from 9 kilograms to 105 kilograms of CO_2e. If cattle is being raised in North America or Europe, it will benefit from better veterinary care and higher-quality feed, which means it will convert feed into meat more efficiently and produce less methane. The same applies to water footprint and land footprint.

1.3.2 Water footprint

Raising animals for food requires large amounts of fresh water, which can cause significant environmental pressures in regions with water stress. Water withdrawals use freshwater taken from ground or surface water sources, either permanently or temporarily, for agriculture. However, even water requirements vary significantly depending on food type, farming techniques and location.

Global animal agriculture accounts for 40% of green and blue water use combined, although the contribution to blue water use is around 6% (Heinke et al. 2020).

Pig meat requires the highest water withdrawal in liters per kilogram of food product; per 1000 kilocalories and per 100 grams of protein. Beef requires less water, although still in considerable amounts. Poultry, on the other hand, requires about 60% less water than beef and pork (Poore and Nemecek 2018).

1.3.3 Land footprint

Agriculture is a major use of land. Half of the world's habitable land is used for agriculture.

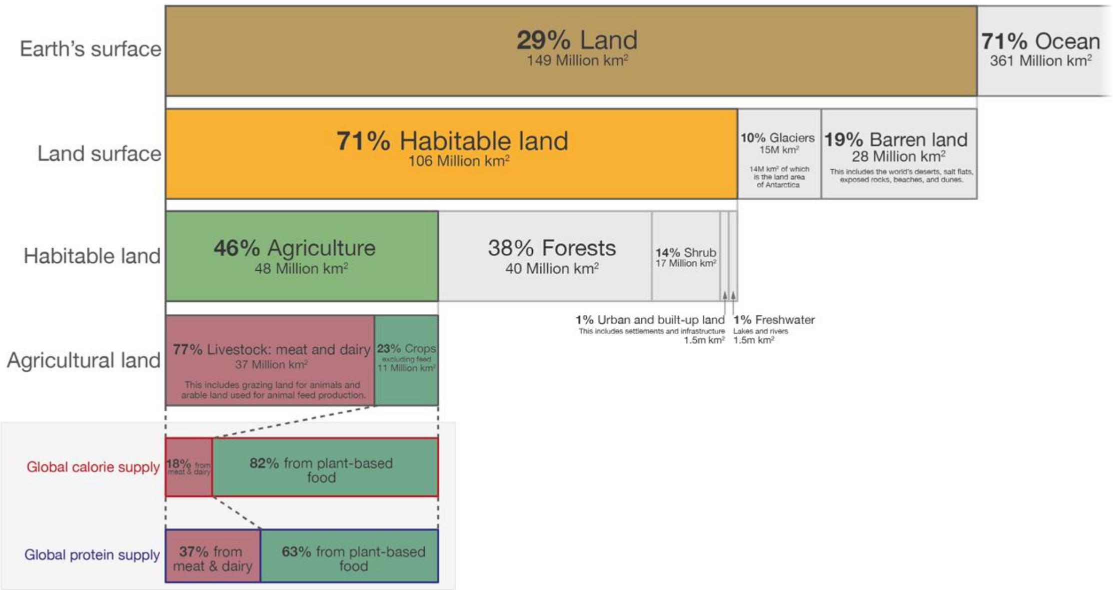


Figure 1.11 Global land use for food production, 2020

In contrast, the built-up area, which includes all settlements and infrastructure, makes up only 1% of the total habitable land. Furthermore, if we combine grazing land with land used for animal feed production, livestock accounts for around 75% of the total agricultural land available. The remaining 23% is devoted to crops for human consumption. While livestock takes up most of the world's agricultural land it only produces 18% of the world's calorie supply and 37% of total protein supply, with plant-based food currently accounting for the vast majority of global calorie and protein supply.

If we look at land area by crop type, wheat, followed by corn, rice and soybeans make up 75% of the total area used to grow crops. This is not surprising given that the crops supply is also essential to meet the nutritional needs of livestock.

The amount of land required to produce food has wide variations depending on the product, and this is especially true when differentiating crops and animal products.

When taking into account land use per kilogram of food product, per 1000 kilocalories and per 100 grams of protein, cereal crops typically have a small land impact. Meat products, on the other hand, use much more land, with beef requiring up to 50 times more area than cereals. However, poultry and pig meat have a land footprint 8-10 times lower than that of beef.

Synthetic fertilizers have enabled unprecedented increases in crop yields as well as the range of geographies where food could be grown. A number of widely-quoted studies have estimated that nitrogen fertilizer now supports half of the world's population. And the share continues to rise as the Haber-Bosch process remains the primary industrial method for the production of synthetic nitrogen fertilizer. However, there are also downsides to synthetic fertilizers. Besides the indirect emissions from production and transportation, crops take up less than half the nitrogen applied to farm fields. Most of the nitrogen runs off into ground or surface waters, causing pollution, or escapes into the air as nitrous oxide. The same process occur when using organic fertilizers. Fertilizer production and use are responsible for about 5% of global greenhouse gas emissions.

Deforestation is responsible for adding 2 billion tons of carbon dioxide to the atmosphere per year while also jeopardizing essential wildlife habitats. Nearly all of global deforestation occurs in tropical and subtropical countries. The expansion of pasture for beef production and croplands for animal feed account for more than 80% of deforestation. The most obvious and immediate impact of deforestation is not the only one to be concerned about. If the trees are burned down, they quickly release all the carbon dioxide they contain but deforestation also causes damage that is harder to see. Since there is a lot of carbon stored up in soil, taking trees out of the ground causes that stored carbon to be released in the form of carbon dioxide. Unfortunately, deforestation does not happen for the same reasons everywhere. In Brazil, for example, most of the destruction of the Amazon rain forest in the past few decades has been caused by the expansion of pastureland for cattle. In Africa, clearing land for food and fuel and forestry are the two main drivers of deforestation. In Indonesia, the vast majority of trees are being cut down for palm oil production. And because food is a global commodity, what is consumed in one country can cause land-use changes in another. For example, second-generation biofuels, which can be produced from non-food crops and industrial waste, may allow for combined farming for food and fuel, providing carbon-free modes of transport. Yet, growing those crops on land that would otherwise be used for human consumption could inadvertently drive up food prices while accelerating the pace of deforestation. However, growing these crops on land that would otherwise be used for food crop production may cause a competition for croplands, with potential undesirable consequences for food prices and food production.

1.3.4 Environmental impact assessment of the Italian meat supply chain

Bragaglio et al. (2018) reported global warming potential values of beef meat equal to 17.62 kg CO_2e and 26.30 kg CO_2e for 1 kg of LW for, respectively, a fattening system and a Podolian beef production system (traditional Italian enterprise). Buratti et al. (2017), instead, reported a value of 18.21 kg CO_2e/kg LW in a conventional system and 24.62 kg CO_2e/kg LW in an organic system. Nguyen et al. (2010a) assessed the environmental impact of beef production in the EU considering different production systems (i.e. intensively reared dairy calves at different slaughter age and suckler herds) obtaining values of GWP that ranged from 16.0 to 27.3 kg CO_2e/kg CW.

As for pig meat, Bava et al. (2017) obtained a global warming potential between 3.25 and 5.25 kg CO_2/kg LW in six farms located in the North of Italy. Unlike other pig production systems, the Italian one is characterized by a high slaughter weight, due to the presence of eight PDO labels of dry-cured ham. This negatively affects the environmental impacts of pig production, as fat deposition negatively affects the feed conversion ratio (Latorre et al. 2003). However, there is also a strong variability due to different management techniques and feeding strategies. Another study on pig production systems reported values varying between 4.81 and 9.75 kg CO_2e/kg CW in the EU context (Nguyen et al., 2010). Other examples of values of GWP results found in the literature for pig meat are: 3.77 kg CO2 eq/kg CW (Dalgaard et al., 2007); 3.34, 4.75 and 5.5 kg CO2 eq/kg CW (Lamnatou et al. 2016; Noya et al. 2017; Winkler et al., 2016); 2.32 and 3.22 kg CO2 eq/kg CW(Mackenzie et al. 2015; Reckmann et al. 2013) and 3.50 kg CO2 eq/kg LW (Djekic et al. 2021). It is worth noting that these values are highly affected by the weight at the slaughtering stage as a lower slaughter weight is associated with lower impacts caused by a shorter rearing time to reach that weight and therefore a reduced feed use per unit of live weight.

With regard to poultry production, Cesari et al. (2017) reported global warming potential values of 3.03 kg CO_2e/kg LW and 3.84 kg CO_2e/kg LW for light and heavy broilers, respectively, highlighting how the Italian poultry meat production system is more impactful than in other countries due to the worse feed conversion ratio of heavy broilers in comparison with light and medium ones, which is probably the main cause of the high GWP per kg of carcass weight of the Italian broiler. Additional measurements found in the literature: from 4.41 to 5.66 kg CO2 eq/kg CW (Leinonen et al., 2012), 2.77–2.79 kg CO2 eq/kg LW (López-Andrés et al., 2018) and 2.2 kg CO_2e/kg LW (Wiedemann et al., 2017).

Animals and plants are being affected by the extra heat and the carbon dioxide that is causing it. Extra heat makes animals less productive and more prone to dying young, which in turn will make meat more expensive. On the one hand, wheat and many other plants grow faster and need less water when there is a large amount of carbon in the air. On the other hand, corn is especially sensitive to heat. While food technology presents significant opportunities for advancing several SDGs, particularly related to environmental sustainability and food security, careful consideration and management of potential trade-offs and challenges are crucial to ensuring that its development and adoption contribute positively to sustainable development.

2 From Lab to Fork: The Promise and Challenges of Cell-Based Meat

Scientists have tried all kinds of ideas for dealing with enteric fermentation and the other sources of emissions discussed above. In most cases, these efforts have failed to achieve the expected results, with the exception of an organic compound that can reduce methane emissions by up to 30%. Due to its frequency of use, however, it is not yet feasible for most grazing operations.

The amount of methane produced by cattle depends a lot on where they lives. So spreading the best breeds and practices to middle- and low-income countries could partially reduce these emissions without any new technology.

Some people propose a more drastic solution: we should just stop raising livestock. Although this sounds like the easiest solution, it represents an idea of development that diminishes the prospects of future generations and undermines the development of other promising solutions to bring the meat industry on track to meet GHG emission reduction targets. Additionally, meat plays a key role in human culture. In many parts of the world, eating meat is a crucial part of festivals and celebrations. For instance, the French gastronomic meal, a customary social practice for celebrating important moments in the lives of individuals and groups, is listed as one Intangible Cultural Heritage of Humanity.

One option to keep enjoying the taste of meat without increasing its environmental impact is plant-based meat, which taste and feels like meat but is made from plants. Barriers to entry into this industry are low due to the reuse of existing technologies and facilities. Many companies already produce and sell large quantities to restaurants, supermarkets, and other businesses, such as Starbucks. Traditional food and meat producers, Nestlé, Kellogg's and Tyson Foods, to name a few, have also entered or announced their entry into the industry, which is also of interest to chemical companies that produce additives used in the production of plant-based meats.

The most promising and innovative technology for meat production is cultivated meat (CM). CM is a sub-discipline of cellular agriculture, which aims to substitute agricultural products derived primarily from animals, materials and individual proteins. Plant-derived products can also be targeted through cellular agriculture techniques.

The promise of cell-based food is manifold: it can address ethical concerns associated with animal welfare, substantially reduce any negative externality that contribute to climate change and environmental degradation, offer a more disease-resistant and consistent products. Furthermore, having more control over the production process may lead to safer, more nutritious, and tastier products than their conventionally produced counterparts.

Manufacturers typically start with a sample of cells from animal tissue. Some cells from the sample are selected, screened, and grown to make a “bank” of cells to store for later use. A small number of cells are taken from the cell bank and placed in a controlled environment that supports growth and cellular multiplication by supplying nutrients and other factors. After the cells have multiplied into billions of cells, additional substances are added to make cells differentiate into various types and assume the desired characteristics. At this stage, the cellular material can be harvested from the controlled environment and prepared using conventional food processing and packaging methods.

The world's first cell-based meat product, unveiled by Professor Mark Post's team at Maastricht University, was cooked and tasted at a news conference in London in 2013. Most of the techniques they used belong to tissue engineering and were pioneered in regenerative medicine. The hamburger in London was mainly the result of trying to grow more material than anyone else had done until then. Starting with stem cells extracted from a biopsy of a cow, Post's team grew 20,000 muscle fibers over the course of three months. Each tiny fiber grew in an individual culture well, suspended in a growth medium. When they were ready, the fibers were removed individually by hand, cut open and straightened out. The $330,000 research was financed entirely by Google co-founder Sergey Brin. According to early indications, Post’s lab meat reduced the need for land and water by 90% and overall energy use was cut by 70%. The hamburger only contained pure protein. It might be good enough as a proof of concept but it was far from a perfect meat substitute. It had no fat or blood, which is where much of the distinctive flavor of meat comes from. The technology was confined to small pieces because the tissue needed oxygen and nutrients to stay alive. In order to produce larger pieces, they need to develop different technologies that have been described in the medical field but have not been applied to meat production yet. In order to produce larger pieces, it is necessary to develop technologies used in the medical field but not yet applied to meat production. This means creating a kind of blood vessels, which could provide fluids, oxygen and nutrients as meat grows (The Guardian, 2013). The future of cultured meat that Mark Post envisioned is as follows, “Twenty years from now if you have a choice […] between two products that are identical and they taste and feel the same and have the same price – and one is made in an environmentally friendly way with much less resources and provides food security for the population and doesn't have any animal welfare connotations to it – the choice will be relatively easy."

Since Mark Post's presentation in 2013, considerable developments have occurred in the commercial landscape, and in late 2020, California-based Eat Just was the first company to obtain the green light to sell its cultivated chicken in Singapore. As of the end of 2022, there are 156 cultivated meat - and seafood - companies, based in 26 different countries. Cultivated meat companies raised $896 million in 2022, bringing all-time investment to $2.8 billion (Good Food Institute, 2022). Some companies are focusing on producing whole cuts of meat, which is a complex, expensive and time-consuming process. Others are combining cultivated meat cells with additional ingredients, which is a simpler, cheaper and easier to scale-up process.

For traditional meat, animals must be raised and slaughtered, and despite productivity gains and reduced animal growth time, production is still dependent on the animal growth cycle. Time to maturity is 18-24 months for beef, 6-7 months for pig meat, and 5-7 weeks for poultry. Traditional meat requires vast amounts of land for raising animals or growing animal feed, as well as infrastructure for animal husbandry, transportation and slaughter. The scalability of traditional animal production requires increasing the number of animals raised, which in turn requires more agricultural land, feed and water. Traditional meat production has relative uniformity in nutritional content and flavor, which are affected by factors over which producers have little control. Animals can develop diseases that can potentially be transmitted to humans, and the use of antibiotics and other medications can contribute to antibiotic resistance.

Conversely, current estimates for cell-based meat suggest a time to maturity from weeks to a few months, depending on the specific technology and desired product. And as technology advances, this period might be reduced. Meat substitutes have a high production efficiency. For example, the protein conversion efficiency of cultured meat is more than 70 percent. Chicken, the most efficient of all livestock, does not exceed 20%. Therefore, cell-based meat also shows enormous potential to achieve higher nutritional output with lower inputs. CM production only requires bioreactors and lab facilities. It can be produced anywhere as long as the facilities are in place, regardless of the country or region, especially in the most vulnerable locations to climate change or where agricultural resources are limited. It is less affected by adverse weather conditions and the impact of climate change because the entire production process takes place indoors. Scaling up involves increasing the size and number of bioreactors, which, in theory, can be more rapidly scalable than breeding and raising more animals. CM provides the potential for greater control over the final product. Producers can potentially adjust taste, texture, fat content, and even nutritional profile to fully meet consumers' needs and preferences. Lab conditions can be more controlled, reducing the risk of diseases. Additionally, there is no need for antibiotics for growth promotion, although sterile conditions are essential.

While many uncertainties still exist, public and private research and commercial developments are accelerating, and more data are becoming available. Scenario building allows trustworthy conclusions to be drawn as early as this stage of technology development. Cultured meat technology is still immature and mostly on a lab or pilot scale. In contrast, conventional meat production systems and supply chains are mature and efficiently organized. So comparing a lab- or pilot-scale technology with a mature, high-efficiency technology provides an unrealistic picture of how the new technology might perform. A common challenge when conducting an ex-ante LCA is the lack of representative data for the evaluated system, which might introduce significant uncertainty into the study (van der Giesen et al. 2020). Despite the difficulties of comparison, providing a picture of the environmental impacts and hotspots of a future production system can help decision making for greater sustainability in the design stages of this system (Villares et al. 2017; Cucurachi et al. 2019).

Sinke et al. (2023) included ambitious benchmarks for meat from intensive farms in Western Europe to ensure that CM is not given an unfair advantage. The comparison made in their study shows the minimum expected benefits from cultured meat. The current global average conventional meat production has footprints 2 to 4 times higher than the ambitious benchmarks (Poore and Nemecek 2018). The ambitious benchmarks for conventional meat are based on intensive and efficient production systems located in the Netherlands (chicken, pork) and Ireland (beef cattle). The growing demand for products with higher animal welfare standards (Scherer et al. 2019) makes some innovations that could reduce product carbon footprints unlikely (e.g., fully indoor farming to capture methane). The boundaries of the system are defined from cradle to gate, excluding packaging, since this is assumed to be the same for all products. For cultured meat, this means after harvest but before leaving the plant. In the case of conventional meat, this means at the slaughterhouse gate. In the case of cultured meat, bioreactors and culture medium storage and mixing tanks are included because they are inherent to this meat production technology and can be considered the replacement of the animal body in the cultured meat production system. The ambitious benchmarks they have set focus on a selection of improvements that have been demonstrated to be feasible and are likely to be implemented on larger scales by 2030. The ambitious benchmarks include the following improvements:

- 15% reduction in methane emissions from cattle through the use of enzymes;
- 5% reduction in ammonia emissions from cattle through increased outdoor grazing;
- Renewable energy at farms and feeding facilities;
- Zero LUC and related GHG emissions associated with soybean production.

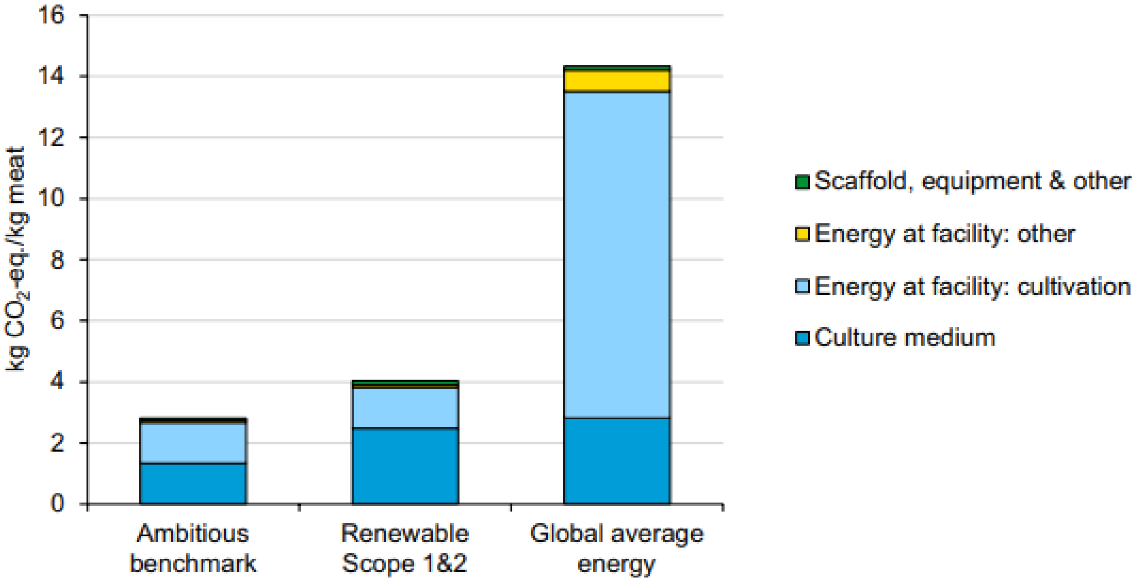


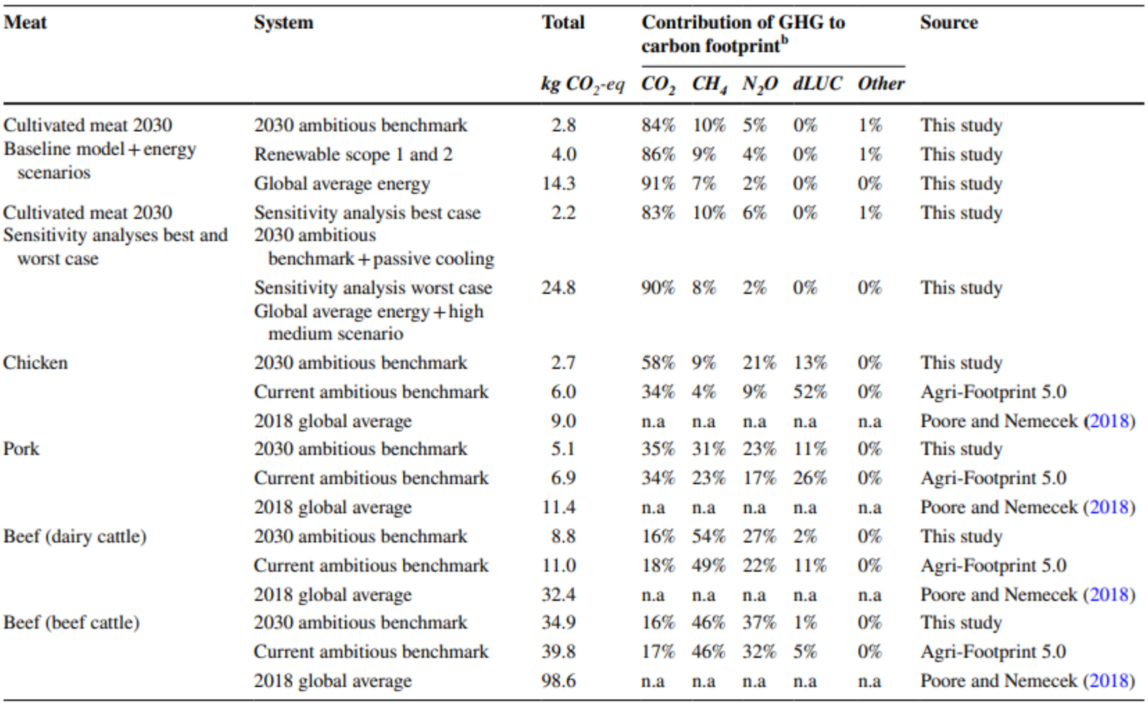
Figure 2.1 Carbon footprint of CM in 2030, baseline scenario with different energy mixes

Results are shown for different energy mixes, which are as follows:

- Ambitious benchmark: Renewable energy for scope 1, 2, and partially 3 (culture medium ingredients, scaffold, filters, water purification)
- Renewable scope 1 and 2: Renewable energy for scope 1 and 2 (at the facility), average mix for scope 3 (upstream)
- Global average energy mix for scope 1, 2, and 3

In the Global Average Energy scenario, the carbon footprint is more than 14 kg CO2e/kg meat, while the Ambitious Benchmark has a carbon footprint of less than 3 kg CO2e/kg meat. In the Renewable Scope 1&2 scenario, the carbon footprint is about 4 kg CO2e/kg meat. The carbon footprint is mainly due to energy use at the facility (scope 1 and 2) and energy use in medium ingredients production. Depending on the electricity mix used and in which scope, the main hotspot is either energy use at the facility or production of medium ingredients.

The main driver of energy use at the facility is energy use by heat exchanger (cooling energy, ~75%), followed by culture medium heating (~10%), aeration, agitation, CIP/SIP, and HVAC (all <5%). The carbon footprint of the culture medium is mainly driven by amino acid production (29-37%, depending on the energy mix during production), followed by recombinant protein (8-29%), glucose (22-29%), and soy hydrolysate (12-16%). On a per kg ingredient basis, recombinant proteins have by far the highest carbon footprint, followed by amino acids production. It seems clear that most of the fermentation technologies currently used have high energy use for some time until the industry is fully mature. Scaffold production has a minor contribution, but it is only used in small percentages of mass (10% of the final product) and is made from relatively low-impact materials. Other factors affecting the carbon footprint are CIP/SIP and water recycling. Equipment has a relatively low contribution for the 20-year lifetime in the baseline scenario.



Meat	System	Total	Contribution of GHG to carbon footprint[b]					Source
		kg CO_2-eq	CO_2	CH_4	N_2O	dLUC	Other	
Cultivated meat 2030 Baseline model + energy scenarios	2030 ambitious benchmark	2.8	84%	10%	5%	0%	1%	This study
	Renewable scope 1 and 2	4.0	86%	9%	4%	0%	1%	This study
	Global average energy	14.3	91%	7%	2%	0%	0%	This study
Cultivated meat 2030 Sensitivity analyses best and worst case	Sensitivity analysis best case 2030 ambitious benchmark + passive cooling	2.2	83%	10%	6%	0%	1%	This study
	Sensitivity analysis worst case Global average energy + high medium scenario	24.8	90%	8%	2%	0%	0%	This study
Chicken	2030 ambitious benchmark	2.7	58%	9%	21%	13%	0%	This study
	Current ambitious benchmark	6.0	34%	4%	9%	52%	0%	Agri-Footprint 5.0
	2018 global average	9.0	n.a	n.a	n.a	n.a	n.a	Poore and Nemecek (2018)
Pork	2030 ambitious benchmark	5.1	35%	31%	23%	11%	0%	This study
	Current ambitious benchmark	6.9	34%	23%	17%	26%	0%	Agri-Footprint 5.0
	2018 global average	11.4	n.a	n.a	n.a	n.a	n.a	Poore and Nemecek (2018)
Beef (dairy cattle)	2030 ambitious benchmark	8.8	16%	54%	27%	2%	0%	This study
	Current ambitious benchmark	11.0	18%	49%	22%	11%	0%	Agri-Footprint 5.0
	2018 global average	32.4	n.a	n.a	n.a	n.a	n.a	Poore and Nemecek (2018)
Beef (beef cattle)	2030 ambitious benchmark	34.9	16%	46%	37%	1%	0%	This study
	Current ambitious benchmark	39.8	17%	46%	32%	5%	0%	Agri-Footprint 5.0
	2018 global average	98.6	n.a	n.a	n.a	n.a	n.a	Poore and Nemecek (2018)

Figure 2.2 Carbon Footprint of GHG profiles of conventional meat and CM

The GHG profiles between conventional and cultured meat are different. In CM production, the main contributor is carbon dioxide, which originates from energy consumption (directly or indirectly), raw materials production and upstream industrial processes. With conventional meat, CH_4 and N_2O make the largest contribution.

Cell-based meat has a carbon footprint comparable to that of chicken and lower than that of pork and beef. Beef cattle has the highest environmental impact for the majority of indicators. This is largely due to methane emissions and the relatively high feed conversion ratio, which requires a large amount of land and agricultural inputs.

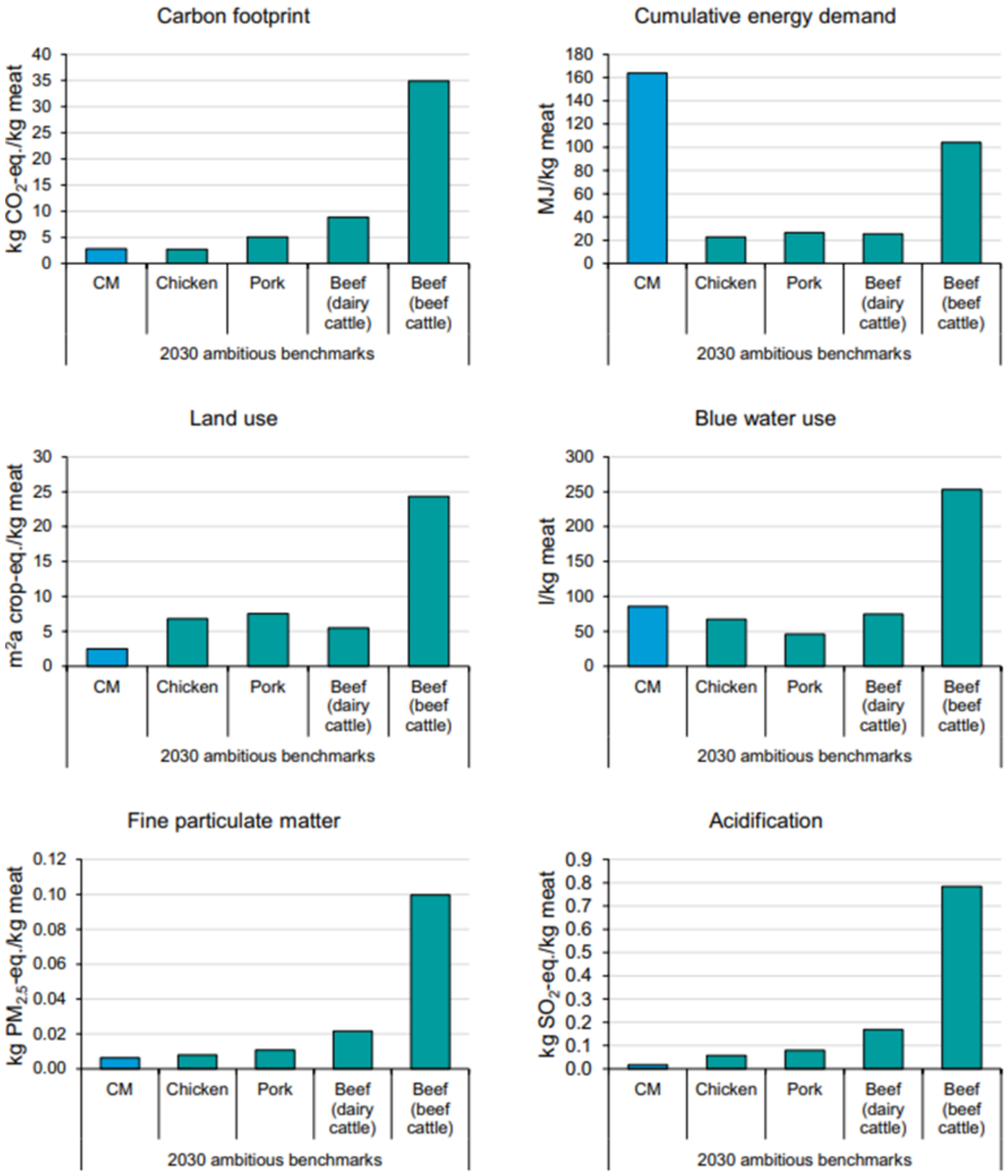


Figure 2.3 Comparison of 2030 ambitious benchmarks for cultivated and conventional meat

The cumulative energy demand is higher than most conventional meats, and is due to energy use at the facility (>70%), followed by energy use for medium ingredients production (25%). The more energy from renewable sources, the smaller this carbon footprint can become.

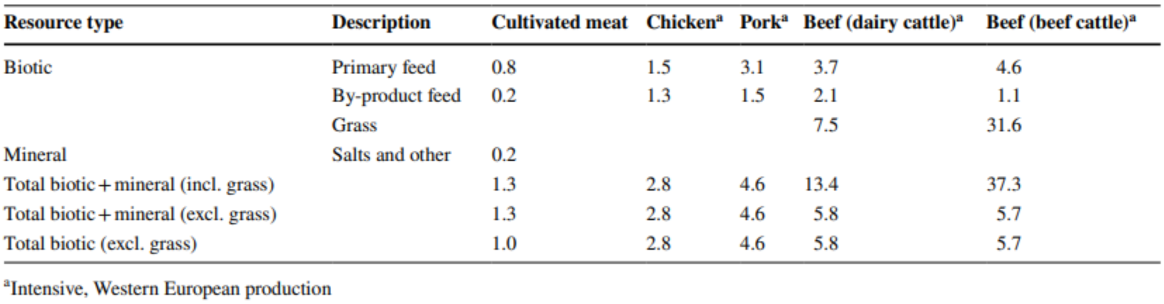
Land use of cultivated meat is undoubtedly lower than that of all conventional meats, which can be explained by the more efficient conversion of crops into the final product, and thus less agricultural land use. Land occupied for renewable energy production (solar and wind) accounts for 10-20% of total land use, showing a trade-off in land use for crop meat. However, overall, the reduction in land use for crops far exceeds the increase in land use for renewable energy production.

Blue water use in cultured meat production is higher for chicken, pork, and beef from dairy cattle, and lower for beef from beef cattle. This result varies according to the percentage of internal water recycling at the facility, which in the ambitious benchmark is 75%. Nearly 50 percent of the water is used in the plant itself (mainly for culture media) and the other half in the supply chain, mainly for the biochemical production of medium ingredients and for the production of renewable energy materials and infrastructure.

Fine particulate matter and acidification results for cultured meat are lower than for all conventional meats. The reason is that ammonia emissions from cultured meat are lower than those from animal systems, because there is no manure and producing cultured meat needs fewer crops and therefore less fertilizer is used. While ammonia is the dominant driver for fine particulate matter and acidification in conventional meat systems, sulfur dioxide and NOx are the main drivers in cultured meat. The latter result from upstream industrial processes, especially the production of chemicals for medium ingredient production and the extraction and processing of materials for the renewable energy infrastructure.

For both marine eutrophication and acidification, nitrogen-related emissions (especially ammonia) are prevalent. The level of freshwater eutrophication is potentially relatively high for cultivated meat. It does, however, depend on the performance of wastewater treatment processes and upstream industrial chemical processes and their treatment.

While for water-related toxicity impact categories conventional meat production scores higher, cultured meat has a greater contribution toward terrestrial ecotoxicity and non-carcinogenic human toxicity than conventional meat. As with freshwater eutrophication, this is driven by upstream production of raw materials for the industrialized, energy-intensive supply chain.



Resource type	Description	Cultivated meat	Chicken[a]	Pork[a]	Beef (dairy cattle)[a]	Beef (beef cattle)[a]
Biotic	Primary feed	0.8	1.5	3.1	3.7	4.6
	By-product feed	0.2	1.3	1.5	2.1	1.1
	Grass				7.5	31.6
Mineral	Salts and other	0.2				
Total biotic + mineral (incl. grass)		1.3	2.8	4.6	13.4	37.3
Total biotic + mineral (excl. grass)		1.3	2.8	4.6	5.8	5.7
Total biotic (excl. grass)		1.0	2.8	4.6	5.8	5.7

[a] Intensive, Western European production

The feed conversion ratio of cultured meat is lower than that of all conventional meats, suggesting that it is a more efficient way to turn crops into meat. This is why the agricultural land use for cultured meat is lower than for conventional meat.

When it comes to biotic FCR, cultured meat is almost three times more efficient than chicken, which has by far the most efficient feed conversion. While the use of mineral feed is negligible for conventional animal production, it is relatively high for cultured meat because of the direct use of salts in the culture medium and the indirect use for the production of amino acids and recombinant proteins. Conventional animals have a relatively high share of by-product feed, relative to cultured meat. Even the primary feed consumption of cultured meat is the lowest, almost twice as low as that of chicken.

Being produced in a closed environment, cultured meat allows for greater control and requires less feed than conventional meat production. This, on the one hand, results in less use of agricultural land and better performance in relation to other environmental indicators related to crop production; on the other hand, it causes CM production to have higher energy demand because some of the energy (calories) used for the animals' biological processes must be replaced by heat and electricity. While electricity and heat can be produced with low environmental impact, the potential for improved sustainability for animal feed is more limited and less scalable.

The controlled environment, direct metabolism, and absence of manure in cell-based meat production ensure limited emissions from the production process. In addition, emissions of ammonia, methane, and nitrous oxide are absent or can be reduced during wastewater treatment or recycling of exhausted media. Conversely, in conventional meat production these emissions are more difficult to mitigate because they are inherent to the biological processes that occur in a less controlled environment.

Since the carbon footprint of cultured meat is mainly determined by carbon dioxide, its potential for sustainability is high because these emissions can be reduced using decarbonized technologies. As the global energy system continues to decarbonize, the average footprint of cultured meat can continue to decrease more significantly than that of conventional meat. In contrast, methane and nitrous oxide emissions from conventional meat production are harder to reduce. Therefore, with the use of renewable energy sources, the carbon footprint of cultured meat can decrease substantially and be as low as that of poultry; if this does not happen, its carbon footprint can be higher than that of pig meat.

In addition to high energy consumption, bioreactor-based cultured meat production and medium ingredients production have relatively high use of blue water and mineral resources. The blue water footprint of cultured meat can be further reduced by increasing recycling at the plan t and efforts in the supply chain. The use of mineral resources in cultured meat production is mainly driven by salts in the culture medium and the production processes of the medium's ingredients. These salts have a relatively low impact per kg, but the amounts add up when they are used in significant volumes. Salts recycling could be an important way to improve resource use and the related environmental indicators.

The main environmental hotspots of cultured meat production are energy use by the facility and the production of culture medium ingredients, where energy use is also essential. Thus, the impact of cultured meat can be considerably reduced by using renewable energy both in the plant (scope 1 and 2) and in the supply chain. Facility energy use is directly up to the cultivated meat producers, who should aim to maximize energy efficiency. The production of cultured medium ingredients becomes important (or even dominant) when the plant is powered by renewable energy. The energy-intensive nature of this stage is largely dependent on the production of recombinant proteins and amino acids and, to a lesser extent, glucose, soy hydrolysate, and HEPES, when used.

From the environmental standpoint, the largest gains come from replacing the highest impact conventional meat products, i.e., meat from beef cattle, with MC. This way it can be an attractive part of a healthy mix of sustainable protein sources, which also includes entirely plant-based options, which are still the most direct way to consume protein with the smallest environmental impact. Finally, hybrid products, part plant-based and part cell-based, will increase the supply of sustainable proteins.

Since prices do not incorporate the environmental impact of a given technology, the current food system is the cheapest one available. So the transition to food products that are simultaneously clean, cheap and safe comes at a cost. Almost all clean alternatives are more expensive than the respective polluting product, service or process. In part, this is due to the reason mentioned earlier: prices do not reflect the relative environmental damage.

The additional cost associated with choosing a more sustainable product, service or process over its more conventional, often less sustainable counterpart is the green premium. Each technology has its own, and its size depends on what is to be replaced and what it is to be replaced with. In very few cases, the green premium is negative, which means that using the clean technology may be less expensive than its dirty counterpart. After obtaining green premiums for clean options, one can begin to evaluate the relevant trade-offs. Calculating green premiums requires some assumptions. However, rather than specific prices, it is important to understand how far the cost of a green technology is from that of its polluting counterpart. So the size of green premiums helps in making decisions about which green technologies to use now and where more research and development is needed to make the clean alternative more competitive.

When the prices of alternative options are available, the calculation of green premiums is simple. However, this is not always the case because there is not a clean counterpart available in all cases. To date, only two U.S.-based companies have authorization to sell their cultured meat products. Good Meat's cultivated chicken is authorized to be sold in Singapore and the United States, while that of Upside Foods can only be sold in the United States. These products are available in a few high-end restaurants, with limited frequency and at relatively high prices. Although price information is not sufficient to make an effective comparison, comparing the production costs of cultured chicken with those of conventionally raised chicken provides useful information about the price competitiveness of cultured meat products. Israeli company Future Meat Technologies produces cultured chicken breasts at a cost of $7.70/pound ($16.9/kg). According to the U.S. Bureau of Labor Statistics, the average retail price of a kilogram of chicken in November 2021 was $3.62.

With the transition to three-dimensional cell culture, mass production of CM is now viable. The current challenges include cell aggregation and the need to create a uniform environment within the bioreactors. For example, temperatures that are too high or too low make the environment inappropriate for cell multiplication, causing them to die. Muscle tissues are essential to give meat its texture. Cultured meat that is currently produced with bioreactors contains no muscle tissue. Therefore, cultivated meat can currently only be processed into minced meat products.

The world's leading chemical and pharmaceutical companies are leveraging their expertise in drugs production to provide scale-up technologies. Indeed, large-scale production of cultured meat requires the knowledge of companies that grow cells in various fields, ranging from regenerative medicine to food fermentation. Studies are underway to recreate the original texture of meat, such as a steak, by including a substitute for muscle tissue. Steps have been taken in this direction in recent years, with the creation of beef muscle tissue by Nissin Food Holdings and the University of Tokyo. A number of startups have also emerged that produce mushroom fiber scaffolds. Many traditional meat companies, including Tyson Foods and Cargill, have invested in cultivated meat startups. As these companies are under pressure from stakeholders to cut down their environmental impact and dependence on animal drugs, improve animal welfare, and prevent contamination and food-borne diseases, they view cultivated meat as a valuable option to offer alongside conventional meat. Cargill believes the cultivated-meat industry has shown promising progress. However, the company sees scaling up production and high costs as continuing challenges and expects that cell-based meat will not be produced in significant volumes before the mid-2030s. The commitment of these food giants to reduce their environmental impact is a huge economic opportunity, as zero-carbon companies will lead the global economy in the coming decades, based on current trends. In all likelihood, conventional food companies, chemical and pharmaceutical manufacturers, and companies connected to food products will be entering the market in the years to come.

In the early days, cultivated meat was prohibitively expensive everywhere. However, with advancements in technology and production scale, costs are dropping, nearing the prices of traditional meat. CM is almost three times more efficient in turning crops into meat than chicken, the most efficient animal. Due to this efficiency and the fact that CM is produced in a closed, manure-free system, its nitrogen emissions and air pollution are lower. CM production is energy intensive, so the energy mix used for production and in the supply chain makes a difference. By using renewable energy, the carbon footprint is lower than that of beef and pork and comparable to the ambitious chicken benchmark. Greenhouse gas profiles are different because CO_2 predominates for cultivated meat and more CH_4 and N_2O are emitted from conventional meats. The climate hotspots are the energy used to maintain temperature in the bioreactors and for the production of the growing medium ingredients.

Although companies can make small quantities of cultivated meat, it is proving much harder to make large volumes at low cost, a transition that is necessary if it is to become competitive with conventional meat. Cultivated-meat companies have to address the risk of contamination, and other technical challenges. Many parts of the process are expensive, including the equipment and the supplies used to feed the cells, keeping production costs relatively high.

CM has a lower potential environmental impact than the ambitious conventional meat benchmarks for most environmental indicators, particularly agricultural land use, air pollution and nitrogen emissions. The carbon footprint is significantly lower than that of beef. The comparison with chicken and pork depends essentially on the energy mix, and increasing the use of renewables can help decarbonize the most energy-intensive supply chain activities. The low agricultural land use of cultivated meat can free up land that could be used to mitigate climate change, foster biodiversity or provide other environmental benefits.

Producers of cultured meat should aim to optimize energy efficiency and further increase the share of renewable energy in every stage of the supply chain, source sustainable feedstocks, and combine low-impact ingredients with high-performance culture medium formulations.

In all likelihood, consumers should consider cell-based meat as a substitute for higher impact meat products.

2.1 Regulatory Responses to Cell-Based Meat Worldwide

As cell-based food technologies and research have advanced, food safety authorities worldwide have been tasked with determining their safety, quality, and labeling requirements.

Singapore became the first country in the world to approve the sale of cell-based meat products in December 2020 when it gave California-based Eat Just the green light to sell its cell-based chicken. It has since approved a number of cultivated food products, as well as a food processing license to Esco Aster to manufacture foods using cell-ag tech. Aussie firm Vow is also expecting Singapore regulators to give the go-ahead for its cultivated quail soon. Aside from setting up its regulatory framework, which has been continually revised to include new feedback from industry stakeholders, Singapore’s government has also poured money into the sector as part of its ‘30% by 2030’ local food production goal. Now housing many homegrown startups like Shiok Meats, and foreign startups like who have chosen the city as its Asia base, Singapore is likely to continue its lead in paving the way for global cultivated meat adoption. When it comes to cell-based meat, the SFA’s approach is to treat it like any other novel food, which are those without a significant history of consumption in Singapore before 1998. To gain approval for sale, these products must undergo an assessment to ensure they meet the standards set by the agency with regard to cell line source, manufacturing process, nutritional composition, and toxicological risks. Furthermore, FSA-approved products need to meet labeling requirements. Singapore's decision can pave the way for other countries, boost investments in start-ups and research initiatives, enhance

Singapore's reputation as a hub for foodtech innovation, and help to build trust and acceptance among hesitant consumers.

In the United States, the regulatory landscape for these products is unique. Instead of one single authority overseeing the entire production process, two federal agencies share the responsibility, each addressing different stages of the cell-based meat's journey from lab to table. The FDA oversees the early stages, which includes the extraction and growth of cells. This role is in line with the agency's extensive experience in regulating cell cultures for medical therapies. FDA is also in charge of ensuring the safety of the substrates, which are the mediums in which cells grow. The establishment of cell banks, which are essentially repositories of cells ready for proliferation, also falls under the FDA's domain. Once the cells are ready to be harvested and turned into food, the oversight shifts to the USDA. Their role involves ensuring that the production process remains safe and the resulting meat is free from contaminants. The USDA’s responsibility continues up to and including the processing and packaging stages, ensuring that cell-based foods are handled with the same care and safety standards as traditional meats.

For food made from cultured animal cells that is produced in other countries, the FDA collaborates with the USDA and other U.S. regulatory agencies to ensure manufacturers meet U.S. import regulations before allowing them on the American market.

One of the most debated topics is how cell-based meat products will be labeled. The USDA oversees this aspect, ensuring that while consumers are provided with clear information, the labeling does not disadvantage or misrepresent either cell-based or traditional food.

Figure 2.4 A prepared dish of Good Meat's cultivated chicken

In late June, California-based UPSIDE Foods and Good Meat, the cultivated meat division of the food technology company Eat Just, became the first cell-based chicken meat producers to receive full approval for commercial sales nationwide. The food and agriculture manufacturing industry has called the latest USDA and FDA approvals a "watershed moment for the cultivated meat, poultry and seafood sector, and for the global food industry." Neither UPSIDE Foods nor Good Meat have a released date of first availability, but they will make sure to bring their products to the American market as soon as possible. Good Meat will launch with restaurateur and chef partner José Andrés while UPSIDE Foods will first reach consumers on the menu of a San Francisco restaurant. In terms of funding, the US government has backed the sector in several different ways. Most notably, the USDA awarded a $10 million grant in 2021 to Tufts University for the creation of a new National Institute for Cellular Agriculture, which was the first-ever government-funded research project in this field. More assistance came in the way of the Global Food Security Research Strategy released in October, as part of Biden’s plan to foster food resilience.

In the European Union, cell-based meat products fall under the scope of the "Novel Food Regulation" (Regulation (EU) 2015/2283), which requires that any food not consumed to a significant degree within the EU before 15 May 1997 be assessed for safety before it can be legally marketed. The European Food Safety Authority (EFSA) is in charge of ensuring that the new food is safe for human consumption. If EFSA gives a positive opinion on the safety of the novel food, the European Commission can draft an implementing act authorizing its placing on the market. While no specific labeling legislation for cell-based meat exists yet, any authorized novel food must be labeled in a way that provides consumers with information regarding any characteristic or property which makes it different from its traditional counterpart. This could be relevant for cultured meat, as consumers may want to know how it differs from traditionally raised meat. If a novel food gets authorization based on proprietary scientific evidence, the applicant can request that such evidence is not used by another applicant for a specific time. While the EU’s food safety rules are among the world’s most stringent, which may mean a slower pace for cultivated products to reach the market, the region is investing in the sector as part of its climate plan. In 2020, the EU’s Farm to Fork strategy included alternative proteins as a key area for a healthy and environmentally-friendly food system. The EU’s core innovation and research funding program Horizon Europe also mentioned cultivated meat and seafood as one out of three of its core pillars, with around €7 million set aside specifically for the sector, with the goal of making cultivated meats more cost-efficient, such as the necessary infrastructure and materials or ingredients, and scale-up efforts. Across Europe, the leading countries advancing cultivated food include the Netherlands, which has made the world’s largest-ever public investment (€60 million) in the cellular agriculture field, and Norway, where authorities have set up a five-year research project into cellular agriculture with €2 million in annual public funding.

Israel is another global leader in the cultivated food industry, with its Innovation Authority’s $18 million injection into a nationwide consortium, involving the country’s top food producers, universities, and research bodies. In addition to research funding, the government has also poured public funds into the sector, contributing over $13 million to early-stage startups and infrastructure. Leading Israeli institutions are conducting cutting-edge research in cellular agriculture. Additionally, several Israeli universities are advancing the knowledge in tissue engineering, a fundamental component of foods made with cultured animal cells. As a result, the Israeli cell-based meat industry has attracted significant local and international investment. The country's reputation, combined with a shift toward sustainable food solutions, has drawn venture capitalists, angel investors, and even traditional meat companies to invest in Israeli cell-based meat startups. As the primary body responsible for public health and food safety, the Ministry of Health plays a crucial role in the regulatory oversight of cell-based meat. As with other countries, novel foods, including cell-based meat, require thorough safety assessments before gaining market approval. The assessment process has to ensure that the cultivated meat products are safe for consumption and free from contaminants. The Standards Institution of Israel is responsible for establishing standards across various sectors, including the food industry. The Israeli government has initiated dialogue between researchers, industry players, and regulators to develop a harmonized approach to oversight. As in other jurisdictions, Israel emphasizes accurate and clear labeling to inform consumers adequately.

As for the United Kingdom, any cultivated meat products is required to go through pre-market authorization from the Food Standards Agency (FSA) as with any other novel foods. There have been some signs that a distinct regulatory framework for cultivated foods could be on the horizon, with one government policy paper suggesting that adopting these changes would be a part of the country’s successful post-Brexit economic plan. Some public funding has been injected into the industry, with the UK Research and Innovation (UKRI) awarding £14 million to twelve projects in May this year, one of which is the Royal Agricultural University’s research into transitioning livestock farmers towards cultivated meat. Previously, the UKRI has backed London-based Multus Biotech, a startup focused on developing cost-effective animal-free growth media to scale affordable cultivated meat production.

In Australia and New Zealand, regulators say their existing Novel Foods Standard will already be able to accommodate foods made through cellular agriculture technologies. This will include cultivated foods that may have used genetic modification technology, which will have to comply with additional regulations. Companies will have to submit their application to the Food Standards Australia New Zealand (FSANZ) for pre-market approval.

Japan is also likely to establish its own new regulatory framework for cultured meat, with its government stating it has already put together an expert team to begin assessing the safety of these products in June 2022. This will be spearheaded by the country's Health, Labor, and Welfare Ministry, whose panel is tasked with deciding the necessary safety precautions for the sector. These moves came after the Japanese Ministry of Agriculture, Forestry, and Fisheries launched a forum in 2020 made up of industry stakeholders, including companies and government agencies, to devise a strategy for building Japan's cellular agriculture ecosystem. In terms of funding, the homegrown startup IntegriCulture Inc. has been awarded a ¥240 million ($2.2 million) grant from the government's Ministry of Economy, Trade and Industry to build its commercial cellular agriculture facility, which has marked a step forward in the company's goal to launch its first food made from cultured animal cells.

Chinese cultivated food industry is pending regulatory approval, which will take three to five years, according to industry representatives. However, potential regulatory agencies that would oversee cell-based meat in China include the National Health Commission and the Ministry of Agriculture and Rural Affairs. Companies are optimistic, as the Ministry of Agriculture and Rural Affairs has listed cultivated meat as a key area for future food manufacturing in its 14th five-year agricultural plan. In addition, the China National Centre for Food Safety Risk Assessment is looking to establish a special group focusing on the regulatory framework of cell-based meat this year. Chinese cultured meat industry is still in its early stage. Technological improvements to reduce production costs is a major objective. Many companies managed to cut down the cost of the culture medium to below CNY 100. But to make cultivated meat commercially available, they need to bring it down to CNY 5 or less. Furthermore, they want to develop cell lines that can be cultured for long periods of time and grow quickly with less nutrition. Firms are not looking at scaling up at the moment as they still need to make the fundamental technology good enough. Therefore, most of the money will be used for improving cell line and culture medium. In addition to laboratories, many companies have set up small pilot plants. However, new rounds of funding will be needed to build more sizeable plants. As part of an event for government, investors and media, CellX served up its first cultivated meat offerings, of which production costs were around 100 yuan ($14). "By the time they will bring their products to market in two or three years, the price could go down 10 times," CEO Ziliang Yang said. The firm opened a pilot facility in Shanghai in August that can produce a couple of tons of cultivated meat a year. The next facility, which will be used for commercial production, is expected to be constructed by 2025 and have the capacity to produce hundreds of tons of meat a year. Although $100 per pound marks significant progress in terms of cost from the first lab-grown hamburger in 2013 it is still a long way from the cost needed to be competitive with traditional meat products. With Singapore and the United States leading the world in terms of regulatory approval for the retail sale of lab-grown meat products, Chinese cultivated meat companies will file applications in both countries with the aim to start selling their products in 2025.

3 The Empirical Analysis

In order to understand the goals and expectations of Italian companies and investors operating in the cultured meat supply chain, interviews were conducted to collect quantitative and qualitative data from companies and professionals carrying out research and commercial implementation in the field of cellular agriculture. The research not only analyzes the economic aspects, which are those of greatest interest for the purposes of the research objectives, but also provides a description of the regulatory framework, which influences the choices and expectations of investors and entrepreneurs. The results of the research will be presented and discussed in the next section.

3.1 Evaluation of the results

In Italy, there are no cultured meat companies, and all organizations in this field fund and/or conduct research. The two most important companies in the development of cultured meat are Bruno Cell and Solaris. Solaris Biotech, founded in 2002, specializes in making fermenters, bioreactors and filtration systems for use in both R&D and production. Its products are used within universities, research centers, as well as in pharmaceutical, nutraceutical, food, environmental, cosmetic, chemical, agricultural companies and for the production of bioplastics and biofuels. Bruno Cell was founded in 2019 and has a Business-to-business (B2B) model. Its core business is to finance scientific research for large-scale production of cultured meat. They have also recently started commercializing cell lines, which are purchased either from companies in this field or from laboratories.

Production scalability is the biggest obstacle for organizations involved in cultured meat. Italy has an excellent technology pipeline because cell line R&D involves many Italian researchers who have already achieved good results, including a fish cell line developed by professors at the University of Tuscia that has received very positive feedback from European cultured meat producers. There are excellent biologists and experts in biotechnology. As far as bioreactors are concerned, Solaris is one of the most advanced companies and supplies its products and services to many of the world's leading companies for cultured food production.

If the industry were fully up and running, cultured meat could replace some widely consumed meats but would be unlikely to match the unique characteristics of local cuts of meat. Therefore, cultured meat stands as an alternative to large-scale meat production. If cultured meat were to catch on, local meat varieties would not disappear. Cultured meat does not compete with traditional livestock farms, which are enough to meet around 5 percent of meat demand and belong to Italian culture. Cultivated meat, on the other hand, is in competition with mass-produced consumer meat.

When it comes to forecasting the uptake of cultured meat, technology plays a key role. Although limited cultured meat products are available in some countries, tons of cultured meat cannot yet be produced at competitive prices. The time horizon is long and much basic research is needed. Many have compared the evolution of cultured meat to the Gartner hype cycle. Bruno Cell predicts that cultured meat will be available on the market at affordable prices in a decade or so.

The position of the current Italian government has also been an obstacle. In a very competitive scenario, as hundreds of startups have emerged in the area of cultured meat in just a few years, where Italian companies and research centers are looking to attract investment from national and international companies and investors, Bruno Cell has found itself at a disadvantage. it is very likely that investors will not choose to invest in cultured meat in Italy, where there is also a concrete risk of finding themselves doing business outside the law. With regard to Bruno Cell, the immediate effect of the government's stance strongly against cultured meat was the termination of previous agreements. The Italian government, however, has not stopped any ongoing activities, and companies are continuing their collaborations with universities and research centers. Bruno Cell also recently won an international call for proposals.

The recent report published by FAO and WHO, Food safety aspects of cell-based food, uses the term cell-based food, with an attempt to involve as many products and technologies as possible. However, to date, there is no single nomenclature, and cell-based meat is referred to by many different names, which relate to how it is produced or its expected benefits.

Currently, there is no specific legislation in Europe but it is still under discussion. The first scientific colloquium took place in Brussels in May where all stakeholders were invited to discuss the opportunities, how to develop this product in Europe, and its case because it has not yet been clarified what the authorization process will be. Producers want this type of product to fall under the novel food regulation, so that the evaluation on quality and safety will follow the existing 18- to 24-month approval process. Others, however, argue that for the type of product, it seems that the novel food regulation is not comprehensive enough. So the possibility of re-discussing the guidelines is being considered, which requires an initiative by multiple member states. During EFSA's Scientific Colloquium on May 11, it was also clarified that when the first application for evaluation by a producer is sent, the existing guidelines will be used because they have already been used for other types of cell-based plant products.

In addition, there are still issues regarding the production process that have held companies back from sending the official request for evaluation. Some of these issues need to be resolved in order to meet EFSA's requirements, while others relate to the final product. For example, some components could leave small residues of GMOs, and in that case, the product would end up in the GMO regulations, which are prohibited. As for issues that do not interfere with EFSA requirements, there are issues with scaffolds, which ensure cell aggregation from start to finish. If this scaffold is added using GMOs, the product risks ending up in the GMO regulations; if they add a fully plant-based scaffold, the product falls in on itself. Instead, the synthetic ones, which seem to deliver the best performance, are made with microplastics that in theory, are removed by cooking. The problem is that, based on some test results, some small residue remains. If the cooking level is reduced, there are too many microplastic residues. Preparing such a product would be more complicated for consumers than a traditional hamburger because they would have to worry about cooking at exactly the right temperature for the right cooking time. There is the issue of supplying fetal bovine serum, although it seems that it can be solved by producing a synthetic serum, which, however, does not have the recombinant protein as a growth factor. So this would have to be added, without using hormones.

At the end of September an important meeting will take place in this regard, and some states, including Italy, will send position papers with which they will try to ask for the possibility of rediscussing the guidelines regarding the evaluation process. So there have been no significant developments since the scientific colloquium in May, which was useful but not definitive. EFSA was keen to remind companies that while trade secrets need to be protected, there is also a need for due transparency for the evaluation to understand which category these products should fall into.

EFSA provides a technical opinion. Let's assume a standard scenario, where a decision to adopt novel food regulation is made at the end of September and a company makes the application a few months later. EFSA's final decision will take at least 18 months. That done, EFSA's technical opinion is acquired by the European Commission and a vote will also be taken based on public consultations, which take into account all stakeholder interests. During scientific colloquium in May, the Commission's referees still had doubts about the transparency of the production process. All stakeholders said they were very keen on objective evaluation of the production process because, due to the issues discussed earlier, they do not want to risk spending 18 months analyzing the production process and then coming to the conclusion that the product under consideration cannot be commercialized.

The Italian government has expressed its opposition to the production, commercialization and importation of cell-based food, although this seems more of a political initiative than a commercial one. The scientific side in Italy has not been blocked and there are a number of universities in Rome, Trento and other places that are dedicated to advancing research. There are no companies that are capable of producing cultured meat.

In the Netherlands, pre-authorization attempts were made in July, which are not very significant but it is only natural that they are promoting this product since they are one of the leading countries in this field. All the cell-based meat products that are currently on the market come from poultry. Also, since exogenous growth factors are used, these products would not be approved in the European Union anyway, which forbids their use for animal husbandry. If adding hormones is not allowed in conventional meat production, it could be the same for cell-based food production in Europe, as European producers would like cell-based meat to fall into the same product category.

The first hamburger presented by Mark Post in 2013 was an experimental product, with the goal of producing an edible food product in the lab that tastes like meat. Many everyday products and ingredients are, in part, synthetic. Mark Post's team tried to synthesize meat. They realized that they could even achieve in vitro cultivation and needed bioreactors to recreate sufficiently powerful metabolic activity. In the first stage, using bioreactors was very expensive and the supply of fetal bovine serum was complicated. They kept improving the process more and more, bringing the production costs down a lot, and other countries then took the same path.

Trade secrets also play a role: if companies cannot use hormones, they must create their own production inputs. After many years and millions spent on their development, producers will not give them away for free. Also, since companies are still in an experimental stage, they will not share much data. On the other hand, since we are dealing with food, we need a lot of transparency to promote food safety. Most likely, the next meeting in late September will not be decisive. It is possible that EFSA will give approval and then the process will be voted down by the Commission. However, receiving a positive technical opinion and being rejected later is not in the interests of either EFSA or the manufacturers, who would rather wait a few more years to make the necessary improvements and have a better chance of the Commission making a favorable decision. The reason why they are progressing at a slow pace is due to the precautionary principle that has always been adopted in Europe. For example, GMOs have always received positive technical opinions and are being produced and sold in other parts of the world. In Europe, however, given the lack of knowledge about long-term effects and the many remaining doubts, food safety authorities have adopted a precautionary approach. Until all doubts are clarified, there is a risk that approval of cell-based food will not follow. If the present roadmap works, EFSA can deliver the first technical opinion by 2025. Even if they decide to speed up the approval process, it will take at least 12 months. Before December-January, companies will not submit any applications because they are not ready yet. It may be that at the September 27 meeting in Brussels some aspects will be clarified, but it is very unlikely that companies will make significant progress in 2 months since they have been working on it for 10 years.

4 Conclusions

Based on the growing demand for meat in the coming years, driven primarily by rising living standards in developing countries, trends in meat consumption, and increased consumer attention to the environmental impact of the current food system and animal welfare, the companies that adapt most effectively and most quickly to these market dynamics will be the market leaders in the future.

To this end, cellular agriculture holds a huge potential. Initially, cultivated meat was prohibitively expensive. However, with advancements in technology and production scale, costs are dropping, nearing the prices of traditional meat. CM has the potential to be a highly efficient, sustainable source of animal protein. Furthermore, it has a lower potential environmental impact than the ambitious conventional meat benchmarks for most environmental indicators, particularly agricultural land use, air pollution and nitrogen emissions. The carbon footprint is significantly lower than that of beef. The comparison with chicken and pork, however, depends essentially on the energy mix. Although cell-based meat production and its upstream supply chain are energy intensive, the use of renewable energy can provide a sustainable alternative to all conventional meats.

Producers of cultured meat should aim to optimize energy efficiency and further increase the share of renewable energy, source sustainable feedstocks, and search for the environmentally optimal culture medium by combining low-impact ingredients and high-performance medium formulations.

Consumers should consider cell-based meat as a substitute for higher impact meat products. It is essential to acknowledge that the cell-based meat industry is still in the proof phase. As the industry evolves, regulations may need to be adapted to accommodate new developments and technologies. The challenge lies in ensuring that these frameworks remain both relevant and effective, without slowing down innovation.

While regulatory approval ensures safety, consumer acceptance towards cell-based meat will play a vital role in its market success. Continued education, clear communication, and stakeholder engagement will be essential in fostering acceptance and understanding.

The collaborative approach between regulatory agencies, industry stakeholders, and consumer groups is essential. As more countries formalize their stances and regulatory pathways, the industry will have clearer guidelines to bring these products to market. The names “cell-based meat”, “lab-grown meat”, “cultured meat”, among others, have been floated around. Although terminology may seem to be of marginal importance, it will, on the other hand, be essential for clear communication and understanding among consumers. While the food safety agencies ensure safety and compliance, the success of cell-based foods will ultimately depend on their acceptance by consumers. Furthermore, as international trade in cell-based foods becomes a reality, harmonizing regulatory standards will be vital to facilitate market access and ensure consistent safety standards.

To date, there are no Italian companies producing cultured meat. Solaris is specialized in the design and production of fermenters, bioreactors and filtration systems that are used both in Research & Development environments and in production areas. Bruno Cell's main activity, on the other hand, is to fund scientific research for large-scale cultured meat production. It has also begun to commercialize cell lines, which are purchased either from companies in the industry or from laboratories. There are also many universities and research centers that are working on research and development. Italian companies and research centers have cutting-edge expertise in the design and manufacture of cultured meat production equipment. In 2021, Solaris was acquired by Donaldson Company, which will leverage Solaris' position in the food and beverage industry to expand into the growing alternative protein market.

The authorization to sell the first cultured meat products in the United States provides a huge economic opportunity for food companies and those operating within the cultured meat supply chain, which are increasing their investments in plant-based and cell-based products. Although cell agriculture research activities are going on in Italy, the country will be less attractive than locations where cell-based meat is already being marketed until these products can be sold in the European Union.

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