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CHAPTER 14

Environmental impacts of meat and meat replacements

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14.1 Introduction

Meat played a pivotal role in human evolution; according to some theories, meat supplying the essential nutrients in a concentrated form freed up space in the gut for energy-rich plant-based food, and this energy enabled the brain to grow substantially (Milton, 2003). However, what enabled early humans to improve their chances of survival over a few million years is no longer necessary nowadays due to various high-quality plant-based foods that were not available back then (Milton, 2003). Instead, overconsumption of animal-based foods has recently become more of a threat to our health and the environment.

Although meat provides several macro- and micronutrients that are essential for good human health, such as high-quality proteins, iron, and vitamin B12 (Godfray et al., 2018), it also contains potentially harmful nutrients, such as saturated fat and cholesterol. Medical research has suggested that meat-rich diets are associated with higher risks of cardiovascular diseases, diabetes, and certain cancers. As a result, studies in high-income Western countries have shown slightly higher mortality rates of people consuming high amounts of red and processed meat (Godfray et al., 2018). Plant-based food can supply the same beneficial nutrients that meat otherwise supplies, although it may require the consumption of a larger variety of foods (Godfray et al., 2018). The EAT-Lancet Commission defined a healthy reference diet from sustainable food systems, considering also the health trade-offs of meat (Willett et al., 2019). They recommend low meat consumption, with a reduction in red meat by more than 50%.

Agriculture, the foundation for food production, is driving the Earth system beyond its planetary boundaries (Campbell et al., 2017), and livestock production plays a central role in agriculture's environmental impacts (Poore & Nemecek, 2018). Among the nine planetary boundaries

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investigated by Campbell et al. (2017), five are at high (already transgressed) or increasing risk (zone of uncertainty). Agriculture is the dominant driver for four of those boundaries and a considerable contributor to the fifth. They estimate that agriculture is responsible for 80% of deforestation and consequently also 80% of terrestrial biodiversity loss for which land use is the main driver, 84% of surface and groundwater consumption, 85% and 90% of nitrogen and phosphorus emissions, and, when accounting for the entire food system, 25% of anthropogenic climate change. More recent estimates suggest that the food system contributes one third to the total anthropogenic greenhouse gas emissions (Tubiello et al., 2021). Reducing the demand for meat can improve agriculture's efficiency and ultimately help solve a dual challenge: feeding a growing and richer population while tackling major environmental challenges.

A transition toward sustainable food systems requires changes in production and diets. Dietary changes are a slow process that can be facilitated (Godfray et al., 2018). Raising awareness and expanding the consumers' knowledge about the environmental impacts of their food choices can help stimulate dietary change (Siegrist & Hartmann, 2019). Likewise, identifying the most promising opportunities for improvement can help efficiently reduce the impacts of meat and meat replacements. This chapter informs about the environmental impacts of meat assessed through life cycle assessment (LCA), compares them to the impacts of conventional and emerging meat replacements, and points to opportunities for improvement of both meat and meat replacements.

14.2 Life cycle assessment of food

14.2.1 Purpose

LCA provides a holistic approach to help transition toward sustainable food systems (Notarnicola et al., 2017). It is a method to quantify the environmental impacts of a product or service throughout its entire life cycle, from resource extraction to waste disposal. Within the food sector, it helps to compare diverse agricultural practices, food products, and diets. It allows identifying and minimizing trade-offs among alternatives, and burden-shifting among life cycle stages or impact categories (Cucurachi et al., 2019; Notarnicola et al., 2017). Scientists, corporations, and policymakers already widely leverage LCA's systematic approach (Cucurachi et al., 2019; Notarnicola et al., 2017), and influential international organizations strongly promote its adoption. For instance, the United Nations Environment

Program hosts the Life Cycle Initiative, and the Food and Agriculture Organization of the United Nations (FAO) initiated the Livestock Environmental Assessment and Performance Partnership. LCA also became the cornerstone for the development of Product Environmental Footprint Category Rules, being developed and aimed to guide the single green market in the EU.

14.2.2 Principles

LCA is a scientific method standardized by the ISO standards 14040 and 14044, consisting of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Cucurachi et al., 2019). In the goal and scope definition, the practitioner determines the purpose of the study and the conditions and assumptions, such as the functional unit and the system boundaries. The functional unit is the basis for comparison; it describes the function the systems of interest deliver (Cucurachi et al., 2019). However, there is no consensus on what an appropriate unit for food is which also depends on the purpose of the study. As the following sections show, a popular functional unit in the LCA of food is based on mass (weight). Since it does not represent the function of food, mass seems an inappropriate unit (Notarnicola et al., 2017). An alternative functional unit, also used in this chapter, is protein content. The system boundaries specify the life cycle stages considered. In practice, LCA studies often do not cover the entire life cycle because it would be too complex and demanding. Instead, they might end at the farm or factory gate, excluding the use phase, even though those impacts might not be negligible (Notarnicola et al., 2017).

For the inventory analysis, the practitioner collects data, models the system of interest as interconnected unit processes, and quantifies the resource use and emissions to the natural environment (Cucurachi et al., 2019). If a system provides multiple functions, such as a cattle farm used for beef and leather production, the analyst must either expand the alternative system to provide the same functions or allocate resources and emissions among the co-products (Notarnicola et al., 2017).

In impact assessment, the practitioner groups the resources and emissions into impact categories and aggregates them. For example, the practitioner groups greenhouse gas emissions (e.g., CO_2, CH_4, and N_2O) into the climate change impact category, converts them into kg CO_2-equivalents by multiplying with their global warming potential (characterization factors in LCA) and sums them up (Cucurachi et al., 2019). Other examples of impact categories relevant to food include land and water use. Despite their importance, many LCA studies only present their inventory and not their potential environmental impacts. As such impacts are site-dependent, they require regionalized characterization models (Notarnicola et al., 2017).

During the interpretation stage, the practitioner draws conclusions and may highlight improvement areas or recommend a preferred option among compared systems (Cucurachi et al., 2019). To prevent misinterpretation, it is important to consider the choices and outcomes from the previous phases, such as the system boundaries, data completeness, selected characterization models, and uncertainties (Notarnicola et al., 2017).

14.2.3 Challenges

The life cycle perspective and the integration of multiple impact categories make LCA an invaluable tool to systematically tackle food's impacts, avoiding burden-shifting. However, LCA shares some of the limitations of other sustainability assessment tools when applied to a complex sector as food: an often narrow scope of existing studies, still immature methods to evaluate important categories, and a lack of data or limited data representativeness.

Past LCA studies of food often considered limited systems and impact categories. Many studies focused only on a few impact categories, especially climate change (Cucurachi et al., 2019). Since LCA is relatively new in the food sector, some impact categories critical for the food sector, such as soil quality and ecosystem services, are largely missing (Cucurachi et al., 2019; Notarnicola et al., 2017). Besides, LCAs do not represent a large part of the world due to geographical biases (Cucurachi et al., 2019). Geographical biases can be critical, considering the site dependence of some impact categories relevant to agriculture, such as land and water use.

The impacts of food systems are more variable than of other economic sectors (Notarnicola et al., 2017). Besides the site dependence of certain impact categories, the inventory data is also more variable. For example, farmers growing the same crop in the same country can still apply different inputs for the same purpose. The variability can come from controllable factors, like management practices, and uncontrollable factors in the environment, like different climates and soil types (Notarnicola et al., 2017).

In contrast to traditional LCAs of well-established systems, prospective LCAs help assess emerging technologies, like the novel meat replacements covered in Section 14.5. Such emerging technologies are still at an early stage of research and development. While prospective LCAs on new technologies have higher uncertainties, they can turn out to be extremely useful to promptly influence technologies' future development. Rather than using existing data from early development stages, for example, lab or pilot stages, LCA practitioners can make predictions about how the technology might develop over time, particularly when reaching a mass scale, to provide a fairer comparison against existing alternatives (Cucurachi et al., 2019).

Ultimately, both LCA and prospective LCA are useful to compare the environmental sustainability of food products, and LCA developers are working on overcoming the challenges. LCAs are getting more regionalized (Mutel et al., 2019), some inventory databases focus specifically on food (e.g. Peano et al., 2012), and new impact assessment methods already tackle some ecosystem services (Alejandre et al., 2019) and aspects of soil quality (e.g. Sonderegger & Pfister, 2021).

14.3 Environmental impacts of meat

14.3.1 Impact variability of meat

Meat has much higher environmental impacts than plant-based foods. Globally, animal products supply 37% of the proteins and 18% of the calories that we consume but use over 80% of the agricultural land and produce almost 60% of food's greenhouse gas, nutrient, and acidifying emissions (Poore & Nemecek, 2018). The impacts of both animal- and plant-based foods vary greatly. However, in terms of greenhouse gas emissions, even the lowest-impact animal proteins result in higher impacts than the average plant-based proteins.

Meat is an inefficient energy source, as energy gets lost during the transfer from plants to a higher trophic level (Godfray et al., 2018). The inefficiency is particularly obvious when animals consume human-edible food like maize or when they graze on pastures suitable for crop production. Livestock also competes with human-edible food when the feed is not human-edible but derived from a human-edible product, like soybeans processed into soybean cakes for animal feed (Mottet et al., 2017). On average, 1 kg boneless meat requires 3.9 kg of human-edible feed and soybean cakes. Meat is also an inefficient protein source. 1 kg of proteins from meat requires, on average, 2.6 kg proteins from human-edible feed and soybean cakes. Grass-fed-only ruminant (animals having a complex stomach with four compartments) systems, like cattle, which produce only 4% of all meat and 8% of beef (Godfray et al., 2018), are especially inefficient in converting feed into food because of their low productivity and the feed's low nutritional density. Still, they are more efficient than industrial monogastric livestock (animals having a simple stomach with a single compartment) systems, like pigs and poultry, to convert vegetal into animal protein. Monogastric livestock systems require less feed but use more human-edible feed and soybean cakes per product unit (Mottet et al., 2017).

The feed composition and efficiency are key drivers of the high variation in the environmental impacts within and among meat types. Ruminants like cattle and sheep use much more land and emit many more greenhouse gases than monogastric animals like pigs and poultry. For scarcity-weighted water use, poultry keeps the lowest impacts among meats, but beef performs, on average, better than pork and sheep meat, following the meta-analysis of Poore and Nemecek (2018). Ruminants show higher variability in impacts than monogastric animals. In terms of impact categories, scarcity-weighted water use has higher variability than land use and greenhouse gas emissions (Poore & Nemecek, 2018).

Conventional, intensive systems often cause lower environmental impacts per product unit than extensive systems. For European pig farms, Dourmad et al. (2014) estimated lower impacts per kg live weight of conventional systems in terms of climate change, acidification, and land occupation than of more extensive, traditional or organic systems. In contrast, they found eutrophication to be slightly lower for organic than conventional systems. For Thai beef farms, intensive systems also showed lower climate change impacts but higher acidification than extensive systems, while eutrophication impacts did not differ significantly (Ogino et al., 2016).

Grazing is especially problematic when it does not occur on natural grasslands but after deforestation. In South America, it drove over 70% of the rainforest loss (Godfray et al., 2018). Under limited circumstances, grazing livestock can benefit climate change mitigation and biodiversity, but the benefits are vulnerable and subject to good management practices (Godfray et al., 2018). For example, livestock can enhance soil carbon sequestration if the grasslands are not yet saturated, but the animals' direct emissions might outweigh the stored carbon. The net benefits are site-dependent. Overgrazing instead leads to additional emissions from the soil. In places where livestock replaces wild herbivores that have disappeared or gone extinct, it can help maintain natural ecosystems, while overgrazing reduces plant species diversity.

14.3.2 Impact hotspots

The livestock sector, the largest anthropogenic source of methane emissions (Godfray et al., 2018), is one of the main sectors driving climate change. Compared to carbon dioxide (CO_2), methane (CH_4) has a higher global warming potential but lower residence time in the atmosphere. Methane emissions mainly stem from the enteric fermentation in the digestive system of ruminants, which explains their much higher climate change impacts. In 2017, agriculture contributed 39% to the total global methane emissions, 71% of which resulted from enteric fermentation (FAO, 2021). The emissions partly also stem from manure management (Flachowsky et al., 2018). Feed production and land use change (whenever relevant) dominate the greenhouse gas emissions of monogastric animals. Processes after the farm gate play a smaller role in the greenhouse gas emissions of meat (Poore & Nemecek, 2018).

Ruminants use much more land than monogastric animals through their grazing on vast areas of pastures. Arable land use for feed production is also higher for ruminants (Poore & Nemecek, 2018), thus confirming another hotspot associated with feed production.

Feed production does not only cause high greenhouse gas emissions (especially for monogastrics) but also dominates water use and greatly contributes to eutrophication. Other water uses, such as drinking water and service water, are generally negligible (Flachowsky et al., 2018). In terms of eutrophication, Dourmad et al. (2014) identified feed production as the main driver across multiple European pig farming systems, except for organic systems where feed production and animal housing (including indoor manure storage) contributed almost equally. Ogino et al. (2016) identified manure-related nutrient emissions as the main driver of eutrophication in Thai beef production systems, followed by feed production in the case of intensive systems.

14.3.3 Opportunities for improvement

While high consumption of animal products is unsustainable, measures such as animal and plant breeding can help reduce impacts. Animal breeding can contribute to higher feed efficiency, lower emissions from enteric fermentation, and higher disease resistance. Plant breeding can aim at higher and more stable crop yields, improved resistance to biotic and abiotic stressors, higher digestibility, and low input requirements, such as water and fertilizers (Flachowsky & Meyer, 2015). In any case, besides improving animal feed, plant breeding would also improve the sustainability of plant-based foods for direct human consumption, which remain more efficient food sources than animal products. Breeding can take different forms, including modern biotechnological procedures, such as artificial insemination of animals or genetic modification of crops. Such modern techniques increase speed and precision but face some public disapproval on ethical grounds and other aspects (Flachowsky & Meyer, 2015).

Feed composition and feeding strategy can also help reduce meat's environmental impacts. The impacts of feed vary greatly by feed type and production location (Flachowsky et al., 2018). Some potential animal feed types do not compete with human food, for example, grass for ruminants if the pasture is not suitable for crop production and, more generally, by-products from the agri-food industry. However, there are also alternative uses for the by-products for the agri-food industry, such as biofuels, biomaterials, bio-adsorbents, and food additives (Nayak & Bhushan, 2019). The nutritional quality and digestibility of the feed are also important, as a lower feed efficiency could cancel out the lower impacts of feed production. Not all by-products are suitable as feed. Certain feed additives can reduce methane emissions from enteric fermentation, but they require further research, and some are banned in the European Union (Flachowsky & Meyer, 2015). Besides, a better understanding of the energy and nutritional requirements of different domestic animal species and ration calculation can contribute to higher feed efficiency (Flachowsky & Meyer, 2015).

The ideal manure management strategy differs among impact categories. There are different options for the treatment, storage, and land application of manure. Some of them include generating electricity and heat or replacing artificial fertilizers. For pig manure, Prapaspongsa et al. (2010) identified anaerobic digestion with natural crust storage as the best management strategy to reduce the impacts of climate change and aquatic eutrophication. In contrast, they identified a scenario without treatment and with a deep injection of manure under the ground as the best management strategy to reduce the impacts of respiratory inorganics and terrestrial eutrophication. The best compromise across impact categories was incineration and thermal gasification with natural crust storage.

Reducing food waste (here, food losses and waste) of meat is also important due to its high impacts per product unit, despite a relatively low share of meat wasted (Vilariño et al., 2017). Effective waste reduction strategies depend on the region. Broadly, low-income countries lose food mainly during agricultural production and postharvest processes, while medium- and high-income countries waste food mainly at the distribution and consumption stages. Technological solutions include, among others, improved storage before, during, and after transport, improved road infrastructure, and smart packaging. Consumers require a better understanding of expiry dates, can better plan their purchases, and use leftovers in food preparation. Retailers and restaurants can reduce waste by donating unsold food and providing more appropriate portion sizes (Vilariño et al., 2017). However, even reducing all food waste, including animal- and plant-based foods, is not as effective as substituting animal-based foods with plant-based alternatives in a US diet (Shepon et al., 2018). In general, any single measure is insufficient for keeping the food system within planetary boundaries. Besides the opportunity areas identified, transitioning toward a sustainable food system fundamentally requires replacing resource- and emission-intensive animal products with more sustainable and efficient plant-based products (Springmann et al., 2018).

14.4 Environmental impacts of conventional meat replacements

14.4.1 Seafood

14.4.1.1 Impacts compared to meat

Fish performs better than meat in some environmental impact categories but worse in others. Poore and Nemecek (2018) show that farmed fish and poultry have similar greenhouse gas emissions. On the upside, farmed fish requires half the land and emits half the acidifying substances of poultry. On the downside, fish has a higher impact on water scarcity and eutrophication than poultry, and within the range of other meat types.

Farmed crustaceans perform worse than farmed fish across multiple impact categories, except for land use. Their environmental impacts, on average, even exceed those of meat for freshwater eutrophication and scarcity-weighted freshwater use (Poore & Nemecek, 2018).

14.4.1.2 Impact hotspots

Fuel use intensity largely determines the environmental impacts of wild-caught animals from industrial fisheries (Avadí et al., 2020). Fuel use causes more than three quarters of the environmental impacts in most impact categories. The fuel, mainly marine diesel, is used to propel the fishing vessels. Its intensity depends on the characteristics of the fishing vessels, such as the fishing gear (e.g., purse seiners or trawlers) and the hull material (e.g., steel, wood, and glass fiber) (Avadí et al., 2020).

Feed contributes the most to the environmental impacts of seafood from aquaculture. Hence, the feed conversion efficiency is critical (Avadí et al., 2020). The feed can come from fisheries with impacts especially from fuel use or from crops with impacts from the use of arable land, irrigation water (Poore & Nemecek, 2018), and pesticides (Henriksson et al., 2015). Pond-based production also contributes greatly to the impacts from aquaculture, for example, through additional water use (Poore & Nemecek, 2018) and runoff of nutrients causing eutrophication of water bodies (Henriksson et al., 2015).

For seafood products from both fisheries and aquaculture, energy use drives the impacts of seafood processing. Packaging materials also play a key role (Avadí et al., 2020).

14.4.1.3 Opportunities for improvement

The high diversity in aquatic animal species consumed by humans results in a wide range of environmental performance (Hallström et al., 2019). Considering climate impacts and the nutritional value of seafood commonly consumed in Sweden, Hallström et al. (2019) recommend increasing the consumption of small pelagic species like sprat, herring, and mackerel, and reducing the consumption of *Pangasius*, crustaceans like shrimps, and flatfishes like plaice. Swedes (and Europeans in general) already commonly consume herring and mackerel but could consume more sprat.

The size of fishing vessels affects the environmental impacts of seafood (Avadí et al., 2020). For example, capturing small pelagics with purse seiners is more fuel-efficient than with trawlers, leading to lower impacts (Avadí et al., 2020). The carbon dioxide emission intensity is lower for small-scale fisheries than industrial ones, although the difference has decreased over time (Greer et al., 2019). There are also regional differences, with the lowest emission intensity in Latin America and the highest in Asia (Greer et al., 2019).

The variability in feed composition offers opportunities for optimization, for example, to lower freshwater use. Feed ingredients can differ a lot in aquaculture, even for the same species. Differences among and within countries currently depend on the farming system, production practice, feed ingredient availability, and farmers' financial means (Pahlow et al., 2015).

14.4.1.4 Gaps

Bycatch and marine environmental impacts often go ignored in impact assessments. Widely used life cycle impact assessment methods, like ReCiPe, do not include yet certain impact categories highly relevant to fisheries, such as overfishing, plastics pollution, and seafloor disturbance (Avadí et al., 2020). Besides impacts on biodiversity, seafloor disturbance due to bottom trawling can be a large source of CO_2 emissions, similar to land use change (Sala et al., 2021). Additionally, proper allocation among marketable products from the multiple landed species requires accurate information on both the targeted species and bycatch (Avadí et al., 2020).

14.4.2 Eggs

14.4.2.1 Impacts compared to meat

The environmental impacts of eggs are generally lower than those of meat, as Poore and Nemecek (2018) confirmed in a meta-analysis for land use, greenhouse gas emissions, acidifying emissions, and eutrophication. Only for scarcity-weighted water use, eggs were within the range of different meat types.

14.4.2.2 Impact hotspots

Similar to meat, the main driver of the environmental impacts of eggs is the feed. Mainly feed composition and feed conversion efficiency drive impacts from feed. Other major drivers are manure management and direct energy and water use in pullet and layer facilities. Egg processing and packaging contribute little (Pelletier et al., 2018).

14.4.2.3 Trade-offs between production systems

The hen housing system makes little difference for the environmental impacts (Pelletier et al., 2018). In Canada, the environmental performance was similar in four out of five housing systems: conventional cages, enriched cages, free-run (indoor), and free-range (with outdoor access). Only organic production caused significantly lower environmental impacts due to less harmful feed production. However, efficiencies at the farm level were not better; for instance, mortality rates were higher than for the other housing systems. Non-cage systems showed a higher variability among facilities, which likely reflects that these new systems are not yet as optimized as the conventional cage systems (Pelletier et al., 2018).

14.4.2.4 Development over time

The environmental impacts of egg production have decreased over time (Pelletier et al., 2018). Automated processes in cage systems, genetic selection, disease prevention (e.g., through vaccines), and altered feed composition improved farm-level efficiencies. The rate of lay and feed conversion efficiency increased, while the mortality rate declined. Likewise, supply chain efficiencies improved. For example, the energy intensity of nitrogen fertilizers reduced, crop yields increased despite lower fertilizer use, and freight transport became more efficient.

While most laying hens in developed countries are kept in conventional cages, they are transitioning toward newer housing systems (Pelletier et al., 2018). The EU banned conventional cages as of 2012, and other Western countries will likely follow.

14.4.2.5 Opportunities for improvement

Eggs have multiple opportunities to reduce impacts along their supply chain, from feed supply to waste management (Pelletier et al., 2018). Optimizing feed can significantly reduce impacts, but it is complex, partly because feed inputs and their geographical origins are quite diverse. Alternatives to reduce the environmental impacts of the feed production should also consider the nutritional content of the feed, as it influences the feed conversion efficiency.

Egg farms exhibit high variability in impacts, especially for non-cage systems. Optimizing farm operations involves multiple factors, such as management practices, technologies, and hen breeds. Besides research and development to identify optimization opportunities, knowledge transfer programs are key to help farmers implement the measures identified. Energy measures such as using renewable energy, implementing energy-efficient housing, and installing LED lighting could further improve the environmental sustainability of egg production.

Waste management can help reduce impacts directly and indirectly. Directly, collecting the manure with manure belt systems and drying it might help to reduce nitrogen losses. The feed, moisture content, and manure management strategies affect the nitrogen use efficiency. Indirectly, the reuse of waste, such as spent hens, could reduce the impacts allocated to eggs.

14.4.3 Tofu and tempeh

14.4.3.1 Impacts compared to meat

Tofu and tempeh, two processed soy products, cause generally lower environmental impacts than meat. In the meta-analysis by Poore and Nemecek (2018), tofu's greenhouse gas emissions, land use, and scarcity-weighted water use are on average 2.6—3.2 times lower than poultry's per mass of protein. However, the authors observed a wide variation. For example, tofu's carbon footprint ranged from 0.9 to 4.5 kg CO_2eq/100 g protein, with an average of 2.0 kg CO_2eq/100 g. In a case study on tempeh from Indonesia, tempeh's supposed place of origin (Liu, 2008), researchers found a carbon footprint of about 1 kg CO_2eq and land use of about 2.6 m^2 per kg tempeh (Wiloso et al., 2019), both several times smaller than poultry's 10 kg CO_2eq and 12 m^2 per kg from Poore & Nemecek's (2018) study.

14.4.3.2 Impact hotspots

For packaged tofu, manufactured in the Midwestern United States, the main driver of climate change impacts was manufacturing (52%), followed by packaging (23%), soybean production (16%), and transportation (9%) (Mejia et al., 2018). The authors neglected greenhouse gas emissions from land use change under the assumption that the soybeans were cultivated on domestic long-established cropland. If there is land use change, the resulting greenhouse gas emissions may exceed those of manufacturing (Poore & Nemecek, 2018).

For tempeh produced in Indonesia, soybean cultivation dominates land use and eutrophication. Transport, especially by road within Indonesia, dominates impacts like climate change, human toxicity, and ecotoxicity. The processing of soybeans into tempeh only slightly affects environmental impacts, with the exception of stratospheric ozone depletion under the conventional production system (Wiloso et al., 2019).

14.4.3.3 Differences between production systems

Since impacts from processing are small, impacts from alternative production systems do not differ much (Wiloso et al., 2019). Hygienic production systems eliminate the use of firewood and have a higher energy and material intensity than conventional systems. Impacts only differ substantially for stratospheric ozone depletion due to the combustion of firewood in conventional production systems.

Climate change impacts for tempeh production are similar in Indonesia and the Netherlands, but the main drivers differ (Wiloso et al., 2019). In the Netherlands, processing has a higher energy intensity and domestic transport is less relevant than in Indonesia. Due to lower ambient temperatures in the Netherlands, fermentation requires additional heat, and the possibly more automated processing in the Netherlands also requires additional energy.

14.4.3.4 Opportunities for improvement

Agricultural expansion into natural areas usually produces carbon emissions from the soil. In contrast, cultivating on long-established agricultural land can potentially sequester additional carbon in the soil. Among other measures, no-till farming can help increase soil carbon sequestration on cropland. In the Midwestern United States, farmers growing corn and soybeans in rotation have implemented no-till practices in recent decades (Mejia et al., 2018). Growing crops locally in Indonesia and switching to efficient local transport modes can help mitigate impacts from transport, a major source of tempeh's environmental impacts (Wiloso et al., 2019). Treating wastewater, using renewable energy, and increasing energy efficiency could further reduce the impacts.

14.4.4 Pulses and nuts

14.4.4.1 Impacts compared to meat

The climate change impacts of pulses and nuts are generally much smaller than those of meat on a protein basis (Poore & Nemecek, 2018). Nuts might even have a net climate benefit, that is, they sequester carbon through land use change. Peas and groundnuts, the most commonly investigated pulses and nuts, use generally less land than meat. Other pulses and nuts have comparable land use to poultry meat, but a wider range of estimates. Compared to pork, the land use of pulses and nuts is clearly lower. Pulses' scarcity-weighted water use lies between poultry's and other meat's. Nuts generally have higher scarcity-weighted water use than any meat; only pork has higher scarcity-weighted water use than groundnuts (Poore & Nemecek, 2018).

14.4.4.2 Impact hotspots

Agricultural production clearly dominates the environmental impacts of pulses and nuts, also because they are typically unprocessed or little processed products. It drives land use, water use, and greenhouse gas emissions (Poore & Nemecek, 2018).

14.4.4.3 Opportunities for improvement

Crop choice and regional optimization are key to lower impacts from pulses and nuts, especially land and water use. Crops' high variations in origin and land and water requirements drive the high variations in crops' impacts. For pulses, land use and land use weighted by net primary productivity vary more among crop types; for nuts, among production origins (Pfister et al., 2011). On the contrary, freshwater consumption and scarcity-weighted freshwater consumption vary more among production origins for pulses and among crop types for nuts (Pfister & Bayer, 2014). For example, the scarcity-weighted freshwater consumption of lentils is about 10 times as high as peas', and pistachios' is more than 15 times as high as groundnuts'. Pistachios grown in Iran, the worldwide largest producer, use about 7 times as much scarcity-weighted water than pistachios grown in Turkey, but about 10 times as little as in Tunisia (Pfister & Bayer, 2014), both among the 10 largest producers in 2019 (FAO, 2021). Among nuts, cashews result in the most greenhouse gas emissions and weighted land and water use; Brazil nuts and walnuts perform relatively well (Cap et al., 2022).

14.5 Environmental impacts of emerging meat replacements

14.5.1 Plant-based meat analogs

14.5.1.1 Definition

Plant-based meat analogs, also called mock meat and imitation meat, are protein-rich foods that mimic meat products (Fresán, Mejia et al., 2019). Such analogs can be made from a wide variety of sources, mainly derived from plants, but may also include animal ingredients. They are usually made from wheat and soy protein and sometimes from legumes, nuts, and vegetables. Animal ingredients include eggs and milk. Meat analogs' final products can be as varied as their sources: burgers and patties, chunks and nuggets, mince and grounds, sausages and links, and cold cuts (Mejia et al., 2020). Examples of plant-based meat analog producers are Beyond Meat from the United States and Vivera from the Netherlands. Many plant-based meat analogs have been on the market for a while, providing useful data to study their environmental impacts, for instance, through LCA (e.g., Mejia et al., 2020).

14.5.1.2 Impacts compared to meat

In general, meat analogs have lower environmental impacts than meat on a mass basis, regardless of the protein source and processing technology (Saerens et al., 2021; Smetana et al., 2015). Exceptions arise in a few impact categories and when using alternative functional units. Water consumption can be higher for plant-based meat analogs than for meat, although earlier studies concluded the opposite (Fresán, Marrin et al., 2019). Gluten-based meat analogs seem to exceed chicken in terms of land occupation, human toxicity, freshwater eutrophication, and metal depletion, while the same does not apply to soymeal-based meat analogs (Smetana et al., 2015). Using kg of digested proteins, gluten-based analogs overall perform worse than chicken.

14.5.1.3 Impact hotspots

The highest overall environmental impacts of plant-based meat analogs stem from energy use for product processing in factories and frying in households (Smetana et al., 2015). Specifically for greenhouse gas emissions, Mejia et al. (2020) estimated that processing is the main source, but they did not consider the consumer stage. Only for cold cuts, agricultural production and transport of food ingredients together contributed more than product processing. Processing was also the main driver of water consumption and marine ecotoxicity, while agricultural production was the main driver of eutrophication and freshwater ecotoxicity (Fresán, Marrin et al., 2019). The high water consumption of meat analogs seems striking. It partly originates from the much higher water requirement of highly processed ingredients compared to the respective primary crops, particularly for isolated soy protein (Fresán et al., 2020). Among meat analogs, higher water consumption seems to be related to diesel fuel use for transportation and electricity use for processing (Fresán, Marrin et al., 2019).

14.5.1.4 Opportunities for improvement

The type of processing technology, such as for the extrusion, represents an opportunity area to improve the environmental impacts of meat analogs. Extrudes can be classified as high-moisture extrudes or low-moisture, texturized vegetable proteins. High-moisture extrusion technologies achieve more useful end-product and lower environmental impacts (Saerens et al., 2021). The processing requirements also affect water consumption, and newer technologies are usually more efficient and can help reduce water consumption (Fresán et al., 2020). Treating process wastewater onsite could reduce the impacts from eutrophication and ecotoxicity on freshwater and marine ecosystems, but it requires more research (Fresán, Marrin et al., 2019).

The protein source can also play a role. For instance, soymeal concentrate was more efficient as a raw material than pumpkin seed flour. Nonetheless, the processing of soymeal concentrate is already well understood, whereas that of pumpkin, as an emerging option, has a larger optimization potential (Saerens et al., 2021). Regarding greenhouse gas emissions, meat analogs based on either wheat, soy, a mix of wheat and soy, or nuts performed similarly; only mixtures containing eggs performed significantly worse (Fresán, Mejia et al., 2019). Regarding water consumption, meat analogs based on rapeseeds, yellow peas, or lupin beans are likely more sustainable than soy (Fresán et al., 2020).

The impacts of meat analogs also depend on the product and preparation types. Cold cuts and minced products emit the least greenhouse gases, followed by nuggets, and last by sausages and burgers (Mejia et al., 2020). Canned products generally emit more than frozen products, but performance can differ among product types (Mejia et al., 2020).

14.5.1.5 Gaps

Impacts by protein source and preparation type and water consumption impacts, in particular, warrant further research. Large differences in environmental impacts might arise from agricultural production and processing requirements of the many plant-based protein sources for meat analogs. Common sources like soy and wheat are better studied than newer ones like pumpkin seeds and lupin beans (Fresán et al., 2020; Saerens et al., 2021). Water consumption differed by two orders of magnitude among studies (Fresán et al., 2020). For greenhouse gas emissions, there was no consistent relationship with the preparation type; for example, canned burgers performed better than frozen burgers, but frozen sausages performed better than canned sausages (Mejia et al., 2020).

14.5.2 Algae

14.5.2.1 Definition

Algae, as used in this chapter, encompass macroalgae (seaweeds like *Saccharina latissimi*, also known as sugar kelp), microalgae (e.g., *Chlorella vulgaris*), and cyanobacteria (e.g., *Arthrospira platensis*, also known as *Spirulina*). Cyanobacteria, also called blue-green algae, are not technically algae (algae are eukaryotes, and cyanobacteria are prokaryotes). For simplicity, we group them together here.

Algae are already commercially available for human consumption, often as food supplements or additives. Still, they have received much more attention in LCA studies for use as bioenergy than as food (Schade & Meier, 2019). Some algae can grow in autotrophic and heterotrophic conditions (Smetana et al., 2017), that is, deriving energy from photosynthesis or uptake of organic carbon. Two general systems to cultivate algae include common open-raceway ponds and emerging closed photobioreactors (Schade & Meier, 2019). Due to the high costs of infrastructure and maintenance, photobioreactors might only be economically viable for high-value products like human nutrition products. They might also be more suitable for human nutrition because they are less prone to contamination than ponds, and the nutritional requirements can be controlled more easily (Schade & Meier, 2019).

14.5.2.2 Impacts compared to meat

Algae's main advantage over meat is their potentially low land requirements; other impacts highly vary across species, production systems, and impact categories. In German conditions, meat replacements based on heterotrophically cultivated *Chlorella* protein powder mixed with soybean meal cause lower environmental impacts than chicken meat on a mass basis. However, if *Chlorella* or *Spirulina* are autotrophically cultivated in photobioreactors, the impacts of the meat replacements are similar to those of beef. Impacts from production in open raceway ponds would even be higher and exceed those of beef (Smetana et al., 2017). Focusing on autotrophic cultivation, Schade & Meier (2019) investigated five microalgae species produced in different climate zones in open raceway ponds or photobioreactors. They concluded that microalgae had, on average, higher impacts than meat.

While microalgae and cyanobacteria show high greenhouse gas intensities, all types of algae are very land efficient (Parodi et al., 2018). On a protein basis, *Chlorella* and *Spirulina* have higher emissions than pork but less than beef. In contrast, sugar kelp has lower emissions than chicken. *Chlorella* and *Spirulina* require much less land than meat, and sugar kelp does not require any land, as it is farmed on the sea. Since sugar kelp extracts nutrients from the water, it can even help mitigate eutrophication of coastal waters (Parodi et al., 2018), to which livestock farming contributes.

14.5.2.3 Impact hotspots

In an LCA study on microalgae and cyanobacteria, Smetana et al. (2017) estimated that nonrenewable energy use, global warming, and respiratory inorganics (leading to human health impacts) had the highest impacts among 13 impact categories assessed. Further studies (Sandmann et al., 2021) confirmed the hotspots in these impact categories.

Across production systems and locations, energy use produces large impacts in most categories (Schade & Meier, 2019). Impacts from energy use particularly stand out in production systems in the Netherlands and indoors in Spain, usually with a contribution between 70 and almost 100%. Energy use depends on the system design and external factors like temperature and solar insolation (Schade & Meier, 2019). Dutch production in autumn or winter resulted in the largest energy use, mainly for heating. Other energy-intensive processes include "aeration and CO_2," "mixing," and "base energy for cultivation."

Infrastructure can also have an evident impact on the environment, especially for production in photobioreactors as opposed to open raceway ponds (Schade & Meier, 2019). Its contribution reaches up to >30% for mineral resource scarcity and cultivation in the Netherlands. Other case studies ignored the impacts of infrastructure. Considering the extensive impacts from energy use in the Dutch cases, infrastructure could even contribute more in other cases.

Water use was highly relevant for cultivation in open raceway ponds (Schade & Meier, 2019). Such ponds use water as process water and through evaporation, and lose water through leakages (Guieysse et al., 2013). Similarly, water use is important for closed systems, which require periodical cleaning and thorough washing with considerable amounts of water (Sandmann et al., 2021).

14.5.2.4 Opportunities for improvement

Scaling up algae cultivation will likely reduce environmental impacts (Schade & Meier, 2019). So far, LCA studies only range from hypothetical models to pilot industrial scales, missing out on large industrial scales. Different system designs of photobioreactors for microalgae cultivation are still emerging (Schade & Meier, 2019). Mariculture, like seaweed farming, is less advanced than land-based agriculture. Opportunities for optimization include breeding and technological development (Parodi et al., 2018).

The algae species, production system, and climate also offer opportunities to improve environmental performance, besides the production scale. Smetana et al. (2017) found that *Spirulina* cause less environmental impacts than *Chlorella*, using the same autotrophic production system. Some species allow heterotrophic cultivation and the use of food waste as a carbon source, both of which would reduce the environmental impacts (Smetana et al., 2017). However, not all the waste sources are equally suitable for the environmentally friendly heterotrophic cultivation. Some species may also allow using wastewater or saline water instead of freshwater (Guieysse et al., 2013). Finally, since different species can have different optimal temperatures, species selection can greatly influence energy use for heating or cooling (Schade & Meier, 2019).

The optimal cultivation system to reduce impacts from energy use depends on the climate of the production site (Schade & Meier, 2019). Open raceway ponds may be more suitable for warm regions, as they do not require active cooling due to the cooling effect of evaporation. In contrast, photobioreactors may be more suitable for cooler regions due to increased light availability. Regions with seasonal variations could reduce impacts by restricting production to specific months. Besides reducing energy demand, providing cleaner energy, for example, from renewables and industrial waste heat, could minimize environmental impacts from energy supply (Schade & Meier, 2019).

Increasing the hydraulic retention time and water recycling rate can reduce water demand for cultivation in open raceway ponds (Guieysse et al., 2013). Both measures influence the volume of process water disposed from the pond, but their potential is limited. Increasing the hydraulic retention time may also increase dark respiration and predation, causing subsequent biomass losses; and increasing the recycling rate degrades the water quality by potentially accumulating salts and pathogens.

14.5.2.5 Gaps

LCA studies on algae for use as food are rare (Schade & Meier, 2019). Investigating the environmental impacts of a greater variety of algae species is lacking (Schade & Meier, 2019). While the studies synthesized here covered cyanobacteria, macroalgae, and multiple microalgae species, a much larger number of algae species exist that have not yet been examined in LCA studies.

The multitude of possible system configurations poses a major challenge for in-depth impact assessments (Schade & Meier, 2019). Especially for the cultivation in photobioreactors, LCA studies cover only a few of the possible system designs. Moreover, heterotrophic cultivation deserves more attention, although it might not be suitable for all algae species and target products (Schade & Meier, 2019). The focus so far has been autotrophic cultivation. As Smetana et al. (2017) have shown, heterotrophic cultivation has lower environmental impacts, besides a lower risk of contamination (Schade & Meier, 2019).

The optimal production system and algae species need to be determined on a case-by-case basis, considering the climate of production sites (Schade & Meier, 2019). No universal trend could be identified in favor of a specific system or species. Given the strong influence of temperature and solar radiation, further research could shed light on the influence of other climate variables, such as wind and rainfall (Schade & Meier, 2019).

The assessment of water use could also be improved and might currently be biased toward arid locations (Guieysse et al., 2013). Water use seems to be sensitive to the hydraulic retention time and process water recycling rate, but realistic upper limits are unknown. Evaporation drives the differences in areal water use across climate zones. Evaporation is highest in arid locations, but higher productivity due to higher temperatures partly counterbalances evaporation losses. The choice of evaporation method can significantly affect environmental impact estimates across locations. More importantly, considering water scarcity can be critical, as the impacts of water use in arid locations might be much greater due to the lower water availability (Guieysse et al., 2013).

14.5.3 Mycoprotein

14.5.3.1 Definition

Mycoprotein is protein derived from fungi. Mushrooms and truffles, which are also classified as fungi, have been consumed in many cultures around the world for a long time. However, due to their low protein content, they are not suitable meat alternatives. Filamentous fungi, in contrast, are rich in proteins and can grow rapidly so that they can better serve as meat alternative (Souza Filho et al., 2019). Mycoprotein is already commercially available. The British company Marlow Foods is a pioneer in the sector. They sell mycoprotein products, based on the microfungus *Fusarium venenatum*, under the brand "Quorn" (Souza Filho et al., 2019). Although already at industrial scale, there is significant room for improvement, as mycoprotein entered the market rather recently compared to conventional meat (Smetana et al., 2015).

14.5.3.2 Impacts compared to meat

Mycoprotein has lower environmental impacts than beef and similar to chicken and pork. For instance, mycoprotein-based mince causes about half the climate change impacts of beef mince. In terms of land and water use, it is more efficient than chicken, considered the least environmentally harmful conventional meat (Souza Filho et al., 2019). While the impacts of mycoprotein and chicken are similar on a mass basis, mycoprotein performs worse than chicken on the basis of food energy or digestible proteins (Smetana et al., 2015).

14.5.3.3 Impact hotspots

The main driver of mycoprotein's environmental impacts is energy use, particularly fossil-fuel energy. Energy use for processing in factories (e.g., fermentation, heat treatments, and centrifugation; Parodi et al., 2018) and frying in households causes about 70% of the environmental impacts (Smetana et al., 2015). Other significant impacts come from the production of components, such as egg white and nitrogen fertilizer needed for cultivating the crops used as substrate, and from transportation (Smetana et al., 2015).

14.5.3.4 Opportunities for improvement

Since the energy use is driving the environmental impacts, improving energy efficiency (Smetana et al., 2015) and using renewable energy (Parodi et al., 2018) can help mitigate the environmental impacts of mycoprotein.

Besides, mycoprotein's controlled production environment offers opportunities for recycling and precise input supply (Parodi et al., 2018). Instead of crops, agro-industrial residues such as lignocellulosic materials without pretreatment could also serve as fungal substrates, which would further reduce the environmental impacts (Souza Filho et al., 2019).

14.5.3.5 Gaps

LCA studies of mycoprotein are scarce. Additional case studies could verify the robustness of past findings. A particular area of uncertainty concerns the amounts of glucose and egg white required for mycoprotein-based products, affecting greenhouse gas emissions (Souza Filho et al., 2019).

14.5.4 Insects

14.5.4.1 Definition

Several countries, especially in tropical regions, have consumed insects for a long time. Western countries, in contrast, only have considered eating insects recently (van Huis & Oonincx, 2017) and remain reluctant to consume them (Onwezen et al., 2021). Worldwide, people consume over 2000 insect species, mostly harvested from the wild. Only about 10 of them are reared as mini-livestock for human food consumption (EFSA Scientific Committee, 2015). Until now, LCA studies cover only a handful of species (Smetana et al., 2021). Besides their use for human consumption, other farmed insects can serve for livestock and pet feed and waste treatment, but those uses are beyond the scope of this chapter. As demand for insects grows, overexploitation and environmental change threaten them in the wild (van Huis & Oonincx, 2017), making insect rearing increasingly important. Insect rearing is, therefore, an emerging industry in Western countries (Smetana et al., 2021); as such, its environmental sustainability is still little known.

14.5.4.2 Impacts compared to meat

Insect-based food has lower greenhouse gas emissions than meat. Insects directly emit greenhouse gases through their respiration, metabolism, and feces; however, they seem to emit less than conventional livestock (van Huis & Oonincx, 2017). While insects have relatively high energy requirements for heating, they have a higher feed conversion efficiency than conventional livestock. They can efficiently use feed for growth because they rely on ambient temperature rather than dietary energy to regulate their body temperature (van Huis & Oonincx, 2017). Moreover, their edible fraction is much higher, as people often eat insects as a whole (Halloran et al., 2016). Thanks to their lower feed demand, insects require less land and water than poultry. In other environmental impact categories, their performance is as good as or better than poultry's (van Huis & Oonincx, 2017).

Most importantly, to actually serve as an alternative to meat, insect products must substitute it. However, most commercial insect-based foods are snacks or novelty products, which do not necessarily reduce meat consumption (Halloran et al., 2016).

14.5.4.3 Impact hotspots

Feed production is the primary driver of environmental impacts in animal agriculture, and insect production is not an exception. This especially applies to land and water use impacts (van Huis & Oonincx, 2017) and to the use of commercial feed (Smetana et al., 2021).

Energy use is another impact hotspot (Smetana et al., 2021). Insect production requires energy at different stages: insect rearing, processing at different degrees, biomass fractionation such as through drying, storage for cooling or freezing (e.g., for fresh products and other products with high moisture contents), and close to consumption for storage, cooking, and indirectly through food waste (Smetana et al., 2021).

14.5.4.4 Opportunities for improvement

As insect production for human consumption scales up, its environmental impacts will likely decrease (Smetana et al., 2019). Moreover, extending insects' use to other ecosystem services, like pollination, further reduces the impacts allocated to their use as food (Smetana et al., 2021).

The wide variety of insect species and feed formulations makes it complex but also offers opportunities to optimize insect production for environmental sustainability. Even the relatively few insect species examined in LCA studies so far already cover four orders (Smetana et al., 2021): (1) beetles (Coleoptera) like the mealworm as the larvae of the yellow meal beetle (Tenebrio molitor), (2) crickets and their relatives (Orthoptera) like the house cricket (Acheta domesticus), (3) bees and their relatives (Hymenoptera) like the European honey bee (Apis mellifera), and (4) flies (Diptera) like the black soldier fly (Hermetia illucens). Unlike the rest, flies are used for feed or waste treatment rather than food. The diverse feed formulations include human-edible food like carrots, chicken feed like fish meal, and even organic waste (Smetana et al., 2021). The feed composition, particularly its protein content, greatly influences growth rates and feed conversion ratios (Halloran et al., 2016). Ultimately, optimal diets depend on the insect species and their nutritional requirements (van Huis & Oonincx, 2017). Like conventional animal farming, insect farming can benefit from genetic selection by developing individuals with traits that offer high efficiencies (van Huis & Oonincx, 2017). Furthermore, the stocking density can influence the feed conversion ratio, as observed for the house cricket (Halloran et al., 2016).

Although optimizing insect diets can improve feed efficiency, it might not always be the most environmentally sustainable measure overall (van Huis & Oonincx, 2017). Optimizing insect diets results in a trade-off between (1) the environmental impacts embodied in the feed (or avoided through waste treatment substitution) and (2) the feed conversion ratio, length of growing cycles, and resulting size of insects (Smetana et al., 2021). Valorizing organic side-streams, such as food losses and waste or animal manure, tend to improve environmental impacts overall (Smetana et al., 2021). Several species can grow on organic side-streams, thereby transforming low-value by-products into high-value proteins and lipids. The suitability of organic side-streams in general and specific by-products depends on the insect species. For example, such an alternative feed seems to be more suitable for mealworms than house crickets (van Huis & Oonincx, 2017). Despite possible benefits of using organic side-streams, legislative restrictions push many insect producers to stick to commercial feed (Smetana et al., 2021). Food safety is a concern. For example, the European Union does not permit the use of organic side-streams like manure and catering waste as feed (van Huis & Oonincx, 2017).

Measures to reduce greenhouse gas emissions could tackle direct emissions and energy use. For direct emissions, ambient conditions such as temperature, humidity, light, and O_2 and CO_2 concentrations determine how much methane insects produce (Halloran et al., 2016). For energy use, the temperature can influence the feed conversion ratio and length of growth cycles (Halloran et al., 2016). The energy requirements, specifically for thermal regulation during insect rearing, depend on the location. Tropical regions offer a more favorable climate, while temperate European and North American regions may require high energy use to achieve suitable temperatures (Halloran et al., 2016). Energy-efficient rooms and equipment can help reduce energy requirements (van Huis & Oonincx, 2017), for instance, through passive heating and cooling, and novel food processing technologies like pulsed electric fields for biomass fractionation.

Besides, to reduce the impacts of the energy requirements, renewables can supply the energy needed with a lower carbon footprint than fossil fuels (Smetana et al., 2021).

14.5.4.5 Gaps

Risks of insect production remain unexplored. For instance, if insects escape, they could invade human and natural habitats, threatening human well-being and biodiversity (van Huis & Oonincx, 2017). They can also cause allergies to workers involved in the production, as another example that requires extensive research (Smetana et al., 2021).

The relative benefits and costs of integrated crop-insect agriculture are also unknown. Many edible insects are harvested from agricultural fields. They provide several valuable ecosystem services like pollination, but also some disservices like crop damage. While LCAs have focused on insect farming so far, they could also help determine if the benefits of incorporating edible insects into crop agriculture outweigh the costs (Payne & Van Itterbeeck, 2017).

14.5.5 Cultured meat

14.5.5.1 Definition

Cultured meat is grown in a laboratory using the stem cells of live animals. It is aimed to closely resemble the taste and texture of conventionally produced meat (Scharf et al., 2019). Cultured meat was first sold in Singapore in December 2020; it was cultured chicken by the US company Eat Just (Carrington, 2020). The few available LCA studies on cultured meat are, therefore, largely based on hypothetical assumptions of how large-scale production processes could look like.

14.5.5.2 Impacts compared to meat

Cultured meat is very energy intensive; still, its climate change impacts are often estimated to be lower than beef's, the meat with the highest greenhouse gas emissions. Compared to other conventional meat, such as pork and chicken, cultured meat's emissions might be higher. While Tuomisto et al. (2014) estimated that cultured meat could have lower climate impacts than poultry, Mattick et al. (2015) estimated in a sensitivity analysis that cultured meat's impacts could be multiple times higher, even approaching beef's. Besides industrial energy, cultured meat requires caloric energy in the form of feed to grow, just like conventional meat. Cultured meat's efficiency to convert feed into food is low, from below 20% in the default case to below 50% in the best case (Mattick et al., 2015), but still higher than conventional meat's.

Cultured meat has lower land use than conventional meat (Mattick et al., 2015; Tuomisto et al., 2014) and slightly higher water use than poultry (Tuomisto et al., 2014). When evaluating 17 impact categories, Smetana et al. (2015) found that cultured meat performs worse than poultry in all, except agricultural land occupation, terrestrial ecotoxicity, and freshwater ecotoxicity. Hence, cultured meat has higher impacts than poultry in all the areas of protection considered: human health, ecosystems, and resources.

14.5.5.3 Impact hotspots

The impact hotspots of cultured meat differ among scenarios. The main driver of energy consumption was cell cultivation, according to Tuomisto et al. (2014), and feedstock processing, followed by bioreactor cleaning, according to Mattick et al. (2015). For Mattick et al. (2015), climate change impacts follow a similar trend as energy; for Tuomisto et al. (2014), the dominant process depends on the feedstock and assumptions about the cell growth. Either feedstock production or cell cultivation contribute most to climate change impacts and water use. Agricultural production of the feedstock uses almost all the land embodied in cultured meat (Mattick et al., 2015; Tuomisto et al., 2014).

14.5.5.4 Opportunities for improvement

Unlike conventional meat, cultured meat has a large potential to reduce climate change impacts (Parodi et al., 2018). Since cultured meat is energy-intensive, switching from fossil to renewable energy sources would greatly reduce emissions. Most of the emissions from livestock production are difficult to mitigate, notably: methane and nitrous oxide, for example, from enteric fermentation, manure management, and fertilizer application.

The scale of environmental impacts depends on the feedstock choice. For instance, cyanobacteria- (still under development) instead of plant-based feedstock would greatly decrease land use, slightly reduce climate change impacts, and slightly increase energy use (Tuomisto et al., 2014).

The controlled environment of cultured meat production offers several opportunities to increase efficiencies and reduce losses, for example, through recycling (Parodi et al., 2018). Besides, feedstock components could be sourced at feed grade, valorizing by-products that might otherwise end up as food waste. Similarly, side streams from cultured meat production (e.g., alanine, ammonia, and lactate) could serve as by-products, thereby lowering the impacts allocated to meat (Scharf et al., 2019).

14.5.5.5 Gaps

Given the low maturity of cultured meat, studies rely on hypothetical assumptions for large-scale production, which may ultimately differ from actual future designs. For example, Tuomisto et al. (2014) assumed that the meat is cultivated in a hollow-fiber bioreactor for 90 days per batch using stem cells from animal embryos and cyanobacteria, wheat, or maize hydrolysate as the feedstock. In contrast, Mattick et al. (2015) assumed that the meat is cultivated in a stirred-tank bioreactor for 11 days per batch using Chinese hamster ovary cells and glucose, glutamine, and soy hydrolysate as the feedstock. They further showed that the impact results are sensitive to the facility size, the biomass increase during differentiation, and the maximum cell concentration.

Existing LCA studies of cultured meat have several gaps in the processes considered. For example, Tuomisto et al. (2014) do not consider cleaning of the bioreactor and production of the basal media, in contrast to Mattick et al. (2015) who, therefore, estimated higher energy use and climate change impacts. Other processes missing in all those studies include cell collection, growth factor production, and waste treatment (Scharf et al., 2019).

The loose cell mass so far considered as the final product in LCA studies underestimates the environmental impacts of a product ready for consumption. It requires further processing for products, such as minced meat. Besides, it requires a longer cultivation time for larger meat pieces, such as steak, further increasing the environmental impacts (Tuomisto, 2019).

14.6 Conclusions and outlook

Reducing meat consumption is essential for a more sustainable food system. Conventional meat replacements like tofu, pulses, and nuts already offer more environmentally friendly alternatives (Fig. 14.1). Emerging replacements also hold the potential to reduce impacts while facilitating the change of consumer choices. For example, cultured meat and plant-based analogs (some are already penetrating the market) can closely replicate meat taste and texture. Therefore, a sustainable food transition can benefit from a dual strategy: promoting the adoption of conventional meat replacements while tackling key challenges of emerging meat replacements.

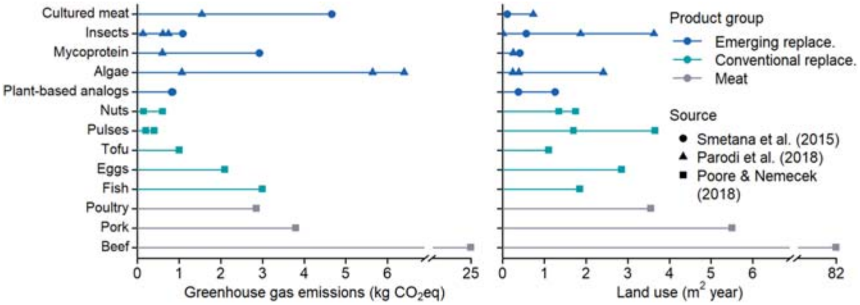

Figure 14.1 Environmental impacts of meat and meat replacements per 50 g proteins.

Adopting emerging meat replacements entails transitioning from inefficient biological systems to potentially more sustainable technological systems. Diverse practices in livestock production systems can certainly help reduce their environmental impact, but their potential is usually limited. As an established market, the livestock sector has sought to improve operations for many years; emerging meat replacements, in contrast, hold the potential to improve production systems considerably. Remarkably, transitioning toward a cleaner energy supply is essential to achieve significant reductions in environmental impacts for new energy-intensive processes.

The performance of meat and meat replacements can vary greatly. Broadly, beef stands out for its extremely high land use and greenhouse gas emissions (Fig. 14.1). Nuts require caution in some locations with water scarcity. Depending on the production design of cultured meat and the algae species, the greenhouse gas emissions of cultured meat and algae may exceed those of pork and poultry. Likewise, depending on the pulse type and the species and production design of insect-based foods, the land use of pulses and insects may be similar to poultry. The greenhouse gas emissions and land use of most meat replacements are considerably lower than that of meat.

To avoid burden-shifting, future research on meat replacements can more routinely assess a broad range of environmental impacts, besides land use and greenhouse gas emissions. Often, the assessments are mass-based, although mass does not represent the function of food. The choice of functional unit, 50 g proteins in Fig. 14.1, influences comparative assessments. So, the functional unit must be chosen carefully, and, at best, impacts for multiple functional units are compared. Next to meat, milk could be replaced with plant-based alternatives. Soy and almond milk show environmental benefits over dairy milk, although trade-offs exist again (Grant & Hicks, 2018).

Besides environmental impacts based on LCA (covered in this chapter), considering broader implications can help define a truly sustainable food system. Life cycle sustainability assessment (LCSA) broadens the impacts assessed from the environmental to social and economic dimensions (Guinée, 2016). Furthermore, the public increasingly recognizes the importance of considering the welfare of the animals used for producing meat products. Scherer et al. (2018) suggested animal welfare as a fourth dimension in LCSA, which is especially relevant to animal-based foods, including some meat replacements like eggs and insects. Chapters 8–11 of this book discuss animal welfare and other ethical aspects of meat and meat replacements.

While emerging meat replacements are improved and scaled up, conventional meat replacements, such as tofu and pulses, can already now greatly increase the sustainability of our food systems. Switching from a typical European diet to a diet without meat and other animal products can reduce greenhouse gas emissions and land use by up to 50% (Hallström et al., 2015). Reduced meat consumption also plays a key role in tackling biodiversity loss (Machovina et al., 2015) and other major environmental challenges.

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Meat and Meat Replacements

An Interdisciplinary Assessment of Current Status and Future Directions

Edited by Herbert L. Meiselman and José Manuel Lorenzo

Provides a balanced view of different perspectives on meat and meat replacements

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About the Editors

Herbert L. Meiselman is an internationally known expert in sensory and consumer research on food, food product development, and food service. He received his training in Psychology and Biology at the University of Chicago, University of Massachusetts, and Cornell University in New York. He retired as Senior Research Scientist at Natick Laboratories where he was the highest-ranking Research Psychologist in the United States government. His accomplishments were recognized with a 2005 Award from the President of the United States. He has served in editorial roles for Food Quality and Preference, Journal of Foodservice, and Appetite. His current interests include the effects of context/environment, emotion, wellness, psychographics, and meals and menus.

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