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Review

Meat substitutes: Resource demands and environmental footprints

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ABSTRACT

The modern food system is characterized with high environmental impact, which is in many cases associated with increased rates of animal production and overconsumption. The adoption of alternatives to meat proteins (insects, plants, mycoprotein, microalgae, cultured meat, etc.) might potentially influence the environmental impact and human health in a positive or negative way but could also trigger indirect impacts with higher consumption rates. Current review provides a condensed analysis on potential environmental impacts, resource consumption rates and unintended trade-offs associated with integration of alternative proteins in complex global food system in the form of meat substitutes. We focus on emissions of greenhouse gases, land use, non-renewable energy use and water footprint highlighted for both ingredients used for meat substitutes and ready products. The benefits and limitations of meat substitution are highlighted in relation to a weight and protein content. The analysis of the recent research literature allowed us to define issues, that require the attention of future studies.

1. Introduction

Food production is one of the most environmentally impactful fields of human activities, with farming activities responsible for 61-81% of greenhouse gas emissions (GHGE), 79% of acidification and 95% of eutrophication of food-related impacts (Poore and Nemecek, 2018). The need to nourish 10 billion people by 2050 and increase calorific energy supply from 30 to 45 exajoules (Bodirsky et al., 2020) challenges the conventional high-calorie diets of high-income countries, which considerably rely on highly processed and animal-derived products (Clark et al., 2018). Further reliance on the business-as-usual approach for feeding the world population would result in the exhaustion of natural resources and almost double overweight and obesity rates (Bodirsky et al., 2020). Meat production is often accused of a large share of environmental impacts (e.g., livestock emits 65 Tg N yr^{-1}, equivalent to one-third of current human-induced N emissions (Uwizeye et al., 2020). In case the tendencies of meat consumption remain, it is also predicted that by 2030 it will be responsible for 37% and 49% of the GHG budget allowable under the 2°C and 1.5°C targets, respectively (Harwatt, 2019). Therefore, it is envisioned that in order to keep within the sustainability targets, diets should change in the direction of meat reduction by more than 50% and plant food consumption increasing by more than 100% (Willett et al., 2019). Such extreme conclusions are associated with the high environmental impacts of animal production chains. Even thought, animal-derived products supply only 17% of global food and around 40-58% of proteins (González et al., 2020), animal production is responsible for an unproportionally large share of environmental impacts. Animal agriculture occupies 77% of all agricultural lands, 30% of all water resources, and 12-20 % of human-induced GHGE (González et al., 2020; Xu et al., 2021). Furthermore, animal manure is responsible for the eutrophication impacts, which are especially deterministic on a regional scale (Wowra et al., 2021).

Despite having a high environmental impact, animal-derived products play an important economic and cultural role in society (Cheah et al., 2020; Milford et al., 2019). According to the statistical and market

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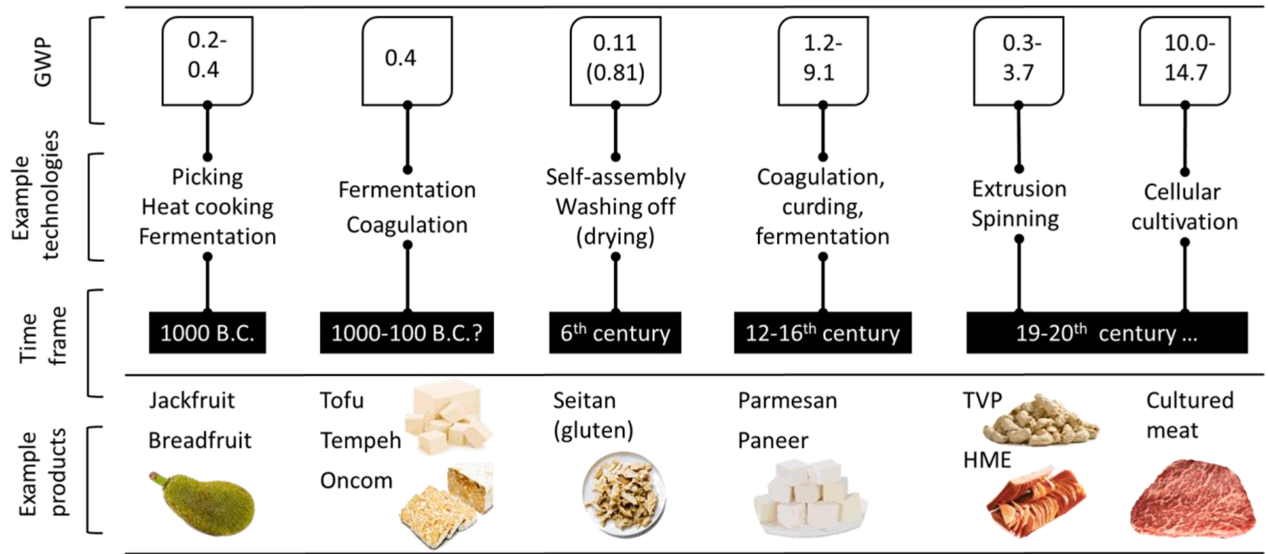

Fig. 1. Historical development of meat substitutes and their global warming potential (GWP); TVP – texturized vegetable protein; HME – high moisture extrusion (Caseificio Caramasche Soc. Coop., 2014; Dalla Riva et al., 2018; Deng et al., 2013; Mejia et al., 2018; Parodi et al., 2018; Saerens et al., 2021; Smetana et al., 2017; Wiloso et al., 2019)

analysis data, the value of the global market is approximated to be more than 1 trillion USD, with the US market covering the biggest part of 838 million USD[1] and the value of the meat industry is expected to grow 20% more till 2025. Besides traditional and economic reasons, meat is a highly valuable source of nutrients (de Smet and Vossen, 2016; Hyland et al., 2017). The importance of meat in current diets is hard to overestimate. Meat is a major source of proteins (28 g of protein per capita daily) and calories (30%) in the current diet of Europeans (Bonnet et al., 2020). It is also demonstrating a rather rapid increase in consumption rates in the last 20 years. However, such a rapid increase would risk exposing the future generations to serious consequences of resource depletion and environmental destruction. Vegetarian and vegan diets, indicated as less environmentally impacting (Fresán and Sabaté, 2019; Rosi et al., 2017), are becoming more popular. However, vegetarians and vegans represent only about 5% of the global population, while the biggest part considers themselves flexitarians, who occasionally consume meat (Kemper, 2020).

Meat products play an important role in society delivering proteins, essential amino acids and microelements (Bohrer, 2017). Meat and animal-derived products play a determining role in the sustainability of diets, challenging the need for future diets to have low environmental impacts (Willett et al., 2019). The major problem of meat consumption is connected not with the fact of consumption itself, but rather with the tremendous rates of overconsumption. Consumption of meat, especially processed red meat, has been clearly correlated with cancerogenic risks and metabolic diseases (Domingo and Nadal, 2017; Lippi et al., 2016; Deoula et al., 2020). It should be indicated that type of meat and type of processing (red versus white, more processed versus less processed), as well as human lifestyle, clearly influence the health risks associated with meat product consumption (Domingo and Nadal, 2017; Lippi et al., 2016). For example, there are quite a lot of synergetic and antagonistic effects between consuming meat products and nutrients. Thus, consumption of foods rich in fiber, vitamins C, D, and E, calcium, and selenium could offset the negative carcinogenic impacts of meat production (Sasso and Latella, 2018). In many cases, reducing the amount of consumed red meat to 25-70 g per day should eliminate these risks (González et al., 2020; Sasso and Latella, 2018). Currently, people in Western countries are consuming five times more meat than 20 years ago, with consumption rates being eight times higher than in developing countries (González et al., 2020). Such rates of overconsumption and overproduction not only lead to obesity, high blood pressure, and increased carcinogenic risks but also to increased environmental impacts. In order to transform the food system into a healthy state (both in terms of nutrition and environmental impact), consumers seek more and more options to enjoy the taste of meat without negative environmental and health consequences.

Meat substitution as a concept is still rather blurry, which might relate to the historical development of the need to supply proteins and later to substitute meat. It is necessary to outline the terms used for the substitutes for meat products. “Meat alternative” is a general term, indicating any source of protein (plant, animal, fungi, or microalgae) that can be used as a replacement for the meat in the meal (Clark and Bogdan, 2019). The term is closely related to the term “alternative protein” and refers mostly to the need to supply proteins and does not include the requirements for precisely mimicking all the nutritional and textural properties (Grossmann and Weiss, 2021). “Meat analog” or “meat substitute” is a more precise term, referring to the products that mimicking meat functionality in terms of processing, nutritional, and sensory attributes (Dekkers et al., 2018; McClements and Grossmann, 2021). Meat analogs are often attributed only to plant biomass as a structural basis and texturized vegetable protein (TVP) technologies, leading to the assumption that such products have beneficial compositions of essential amino acids, low saturated fat, and are cholesterol-free (Samard and Ryu, 2019). However, such attribution does not cover several meat analogs on the market (insect, microalgae, and other meat-based) (Grossmann and Weiss, 2021). “Meat analog” is therefore determined as a quite complex range of products, which should be further differentiated according to the product’s intended application (processing functionality) into: (1) meat analogs mimicking whole muscle tissue, (2) meat preparation analogs mimicking fragmented whole muscle tissue (e.g., minced meat); and (3) processed meat analogs mimicking processed meat products (e.g., sausage) (McClements et al., 2021). This review will account for the potential variations in the level of processing of meat substitutes but will rely on “meat analogs” and “meat substitute” as interchangeable terms referring to physically, enzymatically, or biologically structured meat imitates composed of proteins, fats, carbohydrates, and other substances originated from non-animal sources and less common animal species.

[1] Global meat industry - statistics & facts. Available at: https://www.statista.com/topics/4880/global-meat-industry/

Historically, the substitution of different protein sources for meat followed a few main criteria. The first criterion is associated with local or regional abundance; however, this factor was already considered important prior to the progress of globalization. Availability of local biomass, rich in proteins, resulted in the development of tofu, tempeh, fermented breadfruit products, jackfruit, oncom, seitan, mushrooms (e.g., *Fistulina hepatica, Laetiporus, Lyophyllum decastes*, known as meat mushrooms), paneer, parmesan and other protein cheeses, and insects as products substituting for less available and more expensive meats (Fig. 1). However, globalization increased the availability of meat in many regions of the world, rising the concern about the need to have lower meat consumption and a more balanced diet. Meat availability triggered new criteria for meat substitutes concerning replicability of texture and imitation of meat taste, along with the requirements for improved sustainability. Such requirements triggered the development of new processing technologies aiming for the mimicking of meat texture (Grossmann and Weiss, 2021; McClements et al., 2021; McClements and Grossmann, 2021) and even the replication of meat itself in controlled conditions (Kang et al., 2021). And while the criteria associated with abundance, economic, social feasibility, and techno-functional soundness are well assessed and described in scientific literature e.g., (Dekkers et al., 2018; Siegrist and Hartmann, 2019; van der Weele et al., 2019), assessments of the sustainable impacts (especially environmental) of meat alternatives from a holistic perspective are rather sporadic. Therefore, the aim of the review is to systematize the latest available knowledge on the resource demands and environmental footprints of meat substitutes and analogs.

2. Methods

As the review was oriented on the analysis of recent research trends, it was conducted using the Google Scholar database for the studies published last decade (till 2022). However, a few other studies were also included as they were crucial for the development of some aspects of the research trends. The search of the papers was structured into two phases using two different sets of keywords. The first was aimed at the determining studies dealing with meat substitutes (including production of raw materials) and the second set of selected articles dealt with Life Cycle Assessment, environmental impact, and footprint.

Studies, dealing with meat substitutes, were selected by applying the keywords "meat" and "protein" plus "substitute", "analog". Such a search yielded around 3800 articles. Further inclusion of terms such as "LCA" or "life cycle assessment" or "environmental impact" or "carbon footprint" further limited the number of studies to around 100, from which only 81 studies were published in the last decade.

The review was limited to the original studies published in scientific journals and available in English. Further the title, abstract, and results sections of the articles were analyzed for the availability of quantified data on resource demand and environmental footprints. The analysis narrowed down the articles used in this review to 64 sources, but it also included additional highly referenced studies from older periods. The information was then retrieved for further analysis in the review.

3. Environmental impact and resource use of alternative protein sources

3.1. Plant-based meat substitutes

Plants remain the main source of the biomass used to substitute meat. For plant-based substitutes, these inputs include primary ingredients, e.g., soybeans, wheat, peas, and lupine. Raw grains should go through processing to improve nutrient availability and be considered as meat substitutes. Studies have indicated the use of wet spinning technology as a common method to produce food-grade fibers from soy, pea, and faba beans (Grossmann and Weiss, 2021). Electrospinning is another potential technology for the formulation of textures on nanofiber level (Fonmboh et al., 2021), however, such applications are rather limited to the specific cases, where the inclusion of specific substances (polyphenols or probiotics) in food matrix is required. More industrially applicable are "top-down" techniques applicable to plant protein concentrates and isolates (soy, wheat, pea, lupine, rapeseed, etc.) via low (cooking) and high moisture extrusion (Pietsch et al., 2019), proteins and hydrocolloid mixtures (Kim et al., 2017), and shear cell technology (Cornet et al., 2021). It should be noted that the last technologies currently are mostly applicable on pilot scale only (He et al., 2020). While processing technologies result in similar texturizing products, their applications could be differentiated due to the resource demands and associated environmental impacts.

Table 1
Some environmental impacts of plant proteins fractions used as main matrix for the meat substitution

Product categories	Impact categories	Grains (raw materials)	Flour	Concentrates	Isolates and proteins
Cereals (wheat, oats)	GHGE, $kgCO_2eq.$	0.3-1.0[1,2]	0.5[1]	3.3[1,2]	2.1-8.8[1,2]
	LU, m^2a	2.0-5.5[1,2]	2.0[1]	3.2[1,2]	8.6-33.5[1,2]
Legumes (soy, pea, lupin)	GHGE, $kgCO_2eq.$	0.2-0.6[2]	0.7-2.1[3,*]	1.1-2.0[2] 0.7-1.6[3]	1.8-13.0[1,2] 1.8-5.8[3]
	LU, m^2	3.0[2]	n/a	8.0-20.8[2] 8.2-11.2[3]	13.3-34.7[2] 5.8-12.6[3]

Note: the values in the table are rounded; GHGE – greenhouse gases emissions; LU – land use; WF- water footprint; NRE – non-renewable energy; 1 - (Heusala et al., 2020a); 2 - (Heusala et al., 2020b); 3 - (Lie-Piang et al., 2021); * - values per 1 kg processed crops.

The main matrix ingredients of plant-based substitutes include cereals and pseudocereals (e.g., chia, quinoa) as well as legumes, and mixtures of those. The greenhouse gas emissions of the production of main matrix components range in the scope of 0.2-2.1 $CO_2eq.\ kg^{-1}$ for grains (beans) and flours; 0.7-3.3 kg $CO_2eq.\ kg^{-1}$ for protein concentrates; 1.8-13.0 kg $CO_2eq.\ kg^{-1}$ protein for isolates (and proteins) (Table 1). Land use impacts also demonstrate similar tendency: 2.0-5.5 m^2, 3.2-20.8 m^2, and 5.8-34.7 m^2 for raw materials, concentrates, and isolates respectively. Moreover, when meat substitutes are considered, it should be noted that extensive processing, and the addition of minor components like spices and preservatives usually add 13–26% to the resource demand and therefore increases the environmental impact of plant-based meat (Heusala et al., 2020b; Saerens et al., 2021; Smetana et al., 2021).

Legumes are the most frequently used raw material for the formation of meat substitute structures (Curtain and Grafenauer, 2019). Among them, soybeans, peas, and lupine are the dominant species that are used for this purpose. Level of processing (protein concentration) similarly influences the impact of other legumes used for meat substitutes (Fresán et al., 2019; Heusala et al., 2020b; Lie-Piang et al., 2021). Similarly, water and fossil energy demand can be reduced to 0.7-10.2 % if mild fractionation methods are applied (Heusala et al., 2020b; Lie-Piang et al., 2021).

Protein-enriched products based on nuts are quite common, especially when the delivery of high amounts of lipids is tolerated (e.g., for sports nutrition). Meat analogs based on nut proteins are very rare, as is information on their resource demand and environmental impact. However, it is known that nuts have a high demand for water (Fulton et al., 2019), and it can be expected that the GHGE impacts of nut-based products will be in the range of 2.1 kg $CO_2eq.\ kg^{-1}$ (Fresán et al., 2019). Potato protein, more applicable for other purposes, is used as an additive in meat substitutes and hybrid products and is responsible for GHGE in the scope of 2.2-2.6 kg $CO_2eq.\ kg^{-1}$ protein (Heusala et al., 2020b).

The production of meat substitutes often relies on mixtures of plant

Table 2
Main environmental impacts of texturized and cooked plant-based products used as meat substitutes (basis: legumes, cereals, other vegetable biomass and their mixtures)

Impact categories	GHGE, kgCO2eq.	LU, m^2	WF, L	NRE, MJ
Impact values	2.1[1] 3.1-4.0[4] 1.3-2.4[6] 2.0-13.0[7] 1.5-2.8[*, 7] 22.4[8] 0.5-1.7[9,10] 7.0[11]	1.6-3.7[4] 2.5-6.5[9] 0.4- 3.9[10] 3.5[11]	9.7[4] 106.8[4] 3800.0- 38950.0[5,*] 12100.0[8] 17.0-70.0[9] 180.0[11]	54.0[4] 384.4[8] 6.8-15.8[9] 4.4- 17.7[10]

Note: the values in the table are rounded; GHGE – greenhouse gases emissions; LU – land use; WF- water footprint; NRE – non-renewable energy; 1 - (Fresán et al., 2019); 2 - (Heusala et al., 2020b); 3 - (Lie-Piang et al., 2021); 4 - (Heller and Keoleian, 2018; Khan et al., 2019); 5 - (Berardy et al., 2015); 6 – value indicated for extruded mixtures (Detzel et al., 2021); 7 - (Mejia et al., 2018); 8 - (Saget et al., 2021); 9 – vegan and vegetarian replacers (van Mierlo et al., 2017); 10 – burger patty (Saerens et al., 2021; Sergiy Smetana et al., 2021); 11 - plant-based burger (Goldstein et al., 2017); * - value indicated for general category of plan-based meat substitutes.

and animal raw materials. If the plant base composition (mix of soybean and wheat concentrates) is reported to have an impact of around 2.3 kg CO_2eq. kg^{-1} (Fresán et al., 2019) then the addition of animal-derived products (e.g., eggs) increases the impact to 2.7 kg CO_2eq. kg^{-1} (Fresán et al., 2019). However, the increase in impact would depend on the amount added (Table 2). More complex convenience mixtures consisting of plant protein concentrates or isolates (soy, pea), plant oils, additives and spices further increase the GHGE to 3.1-4.0 kg CO_2eq. kg^{-1}, energy use to 53.98 MJ kg^{-1}, land use to 1.6-3.7 m^2a eq. kg^{-1}, water footprint to 9.73 liter eq. kg^{-1} (Heller and Keoleian, 2018; Khan et al., 2019). "Impossible burger" (based on soy protein concentrate) has increased water consumption to 106.8 liter eq. kg^{-1} (Khan et al., 2019). Even higher rates of water footprint are indicated for the average plant-based meat substitute in scope of 3.8 m^3 kg^{-1}, which might be connected with the use of isolates, which are reported to have high water footprint (38.95 m^3 kg^{-1}) (Berardy et al., 2015). Therefore, the impact of meat substitutes is determined by the impact of the main ingredients in the matrix mixtures.

Meat substitutes are frequently evaluated at the point of sale for convenience products. Aggregation of data from a few factories in the US on the production of 57 meat substitutes (burger patties, sausages, nuggets, cold cuts and grounded mass) based on soy, wheat, gluten, vegetable oils, and spices with salt in different preservation states (frozen to dried) indicates the average carbon footprint of 2.19±0.65 kg CO_2eq. per kg of product (Mejia et al., 2020). Similar product (extruded mixtures) from white lupine protein isolate and buckwheat flour or amaranth flour had similar GHGE of 1.3-2.4 kg CO_2eq. kg^{-1} product or 4.3-8.0 kg CO_2eq. kg^{-1} protein (Detzel et al., 2021), as well as ready for consumer handling tofu: 2-13 kg CO_2eq. kg^{-1} protein (Mejia et al., 2018). 1 kg of cooked pea meatballs produced in Germany were characterized with 22.35 kg CO_2eq., 1,698.6 points land use, 384.42 MJ energy use, 12.1 m^3 deprived water scarcity, and 0.013 kg Peq. freshwater eutrophication kg^{-1} protein (Saget et al., 2021), with major impact on resource use (31-85% depending on the category) coming from consumer's cooking. Van Mierlo et al. in their study (van Mierlo et al., 2017) indicated the aggregated ranges of environmental impacts for vegetarian and vegan-based meat substitutes, separating them as chicken and beef replacers (all falling in the ranges of 0.59-1.35 kgCO_2eq./kg for climate change; 2.52-6.51 m^2 per year and kg for land use; 0.017-0.07 m^3 kg^{-1} for water use and 6.78-15.78 MJ kg^{-1} for fossil fuel depletion). Recent LCA studies comparing different burgers on the market (Sergiy Smetana et al., 2021) and designing similar production conditions (Saerens et al., 2021) highlighted the low environmental impacts and resource demands of plant-based raw burger patties (113 g). The GHGE per burger patty were 0.17 kg CO_2eq. (pea-based from supermarket), 0.19 kg CO_2eq. (soy-based from supermarket), 0.06-0.1 kg CO_2eq. (pilot produced soy-based), 0.08-0.1 kg CO_2eq. (pilot produced pumpkinseed-based). Similarly, the impacts of all the products fell in the range of 0.5-2 MJ for non-renewable energy consumption and 0.05-0.44 m^2org.arable for land use per 113 g of raw patty. Impacts in the resource scarcity were 8-14% of those highlighted for beef burger patties. The results correspond well to the previous GHGE of a plant-based burger: 6.94 kg CO_2eq. kg^{-1}, water use: 0.18 m^3 kg^{-1} and land use: 3.5 m^2org.arable kg^{-1} (Goldstein et al., 2017).

Plant-based meat substitutes, in general, have a low resource demand and environmental impact. It is determined by the impact of raw materials and other main components in the product matrices and their level of processing. A higher level of processing and the inclusion of a longer list of components usually increase the impact of meat analogs, calling for minimally processed plant-based meat substitutes.

3.2. Animal-based substitutes (fish, less common animals and milk-based)

Meat products can be substituted not only with plants but also with more similar types of biomass. Use of fish, meat of less common animals (rabbits, seals, kangaroo, and other game animals like wild boars and deer) or milk proteins are common strategies. It is often considered that alternative animal protein sources from species that are abundant and adopted to local conditions (e.g., kangaroo in Australia and deer in the Northern Hemisphere) can contribute to environmentally feasible human nutrition, by having a lower impact than conventional livestock (Goulding et al., 2020; Hadjikakou et al., 2019). A recent study (Fiala et al., 2020) indicated that red meat (beef) can be sustainably replaced by local wild red deer (6.9 kg CO_2eq. kg^{-1} of meat), but only if the wild red deer is considered as an elementary flow without additional environmental burden (e.g., enteric methane emissions). In this case, travelling and hunting is responsible for 85% of the impact. When the enteric fermentation is included in the accounting the impacts increase to 20.1-47.1 kg CO_2eq. kg^{-1} of meat (Fiala et al., 2020). Other meat types could also be quite competitive if they are "extracted from nature in local conditions" such as seal and whale meat in Greenland (4.5 kg CO_2eq and 2.1 kg CO_2eq. kg^{-1} meat respectively) (Ziegler et al., 2021). Hunted meat amount, at the same time, depends on a quota system that varies between states, which from one side is defined according to the potential of the hunted population for reproduction and from the other side indicates that such a source of meat is quite limited to meet the demand of the entire population on a constant basis. Overhunting of wild animal species has a direct negative impact on biodiversity, particularly for slow-reproducing species, such as whales, etc. (Ingram et al., 2021). At the same time, the removal of wild animals from the food system (often interlinked with rural areas (Bélanger and Pilling, 2019)) and their replacement with conventionally produced meat could result in tremendous negative environmental consequences associated with land use change and biodiversity loss (Booth et al., 2021).

Agriculture-based meat production (rabbits, ostriches) results in higher impacts for alternative animals, coming close to the impact of conventionally farmed livestock. Thus, rabbit meat is indicated to have an impact in the scope of 11.5 kg CO_2eq. kg^{-1} meat or 51.4-83.2 kg CO_2eq. kg^{-1} protein (Cesari et al., 2018; Jiang et al., 2020), while ostrich farming could be less impactful than poultry production (impact of 1.68 kg CO_2eq. kg^{-1}) (Ramedani et al., 2019).

Fish has been long considered a potential substitute and a high-value protein product. It should be noted that aquaculture (similarly to animal husbandry) is a source of proteins with very diverse environmental impacts. In general, GHGE are lower for fish products than for meats; however, if recalculated per 1 kg of proteins, the average GHGE of farmed fish (~60 kg CO_2eq. kg^{-1} protein) is similar to that of poultry meat (~59 kg CO_2eq. kg^{-1} protein) (Poore and Nemecek, 2018). The environmental impacts of wild-caught fish are lower than those of

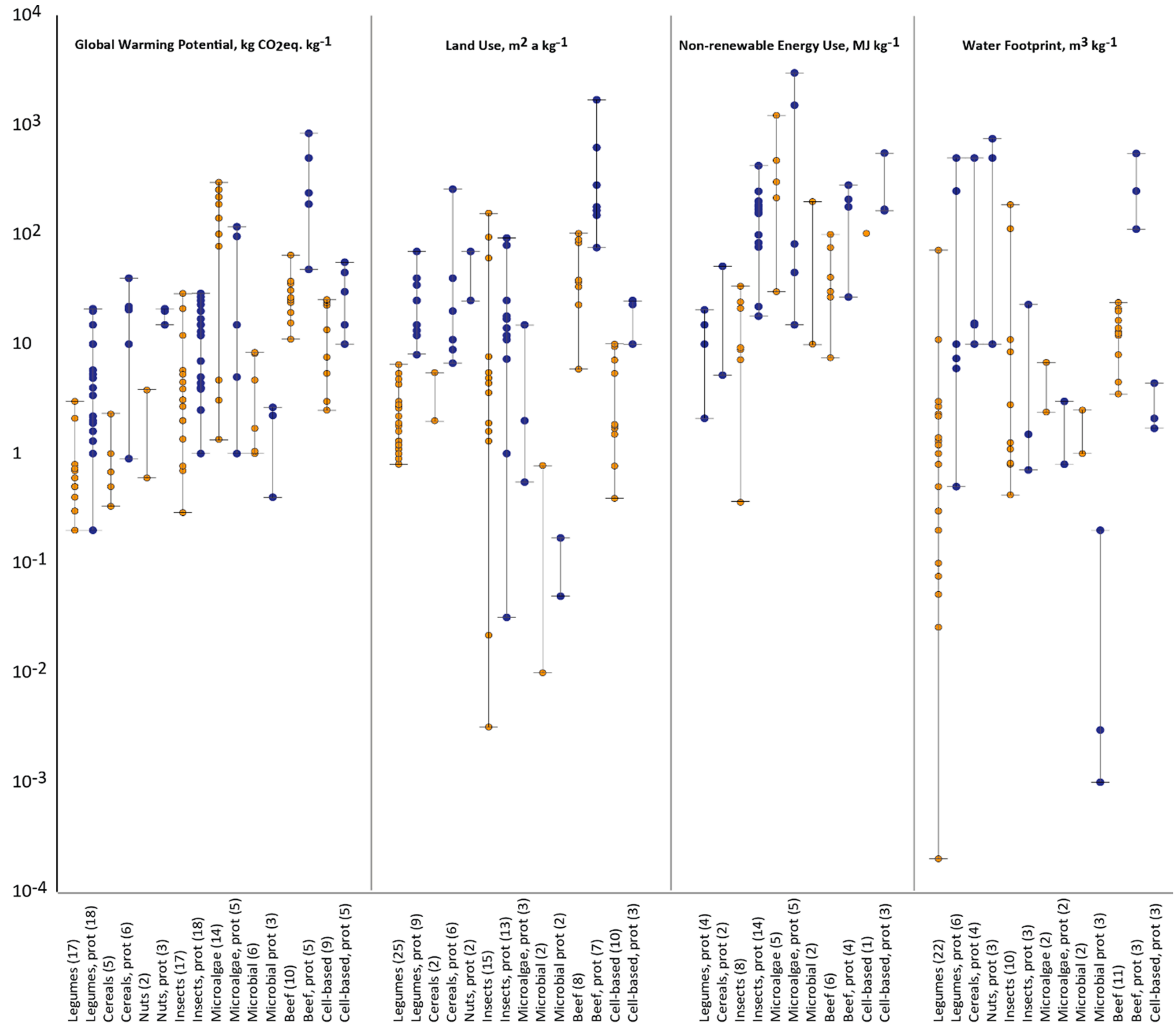

Fig. 2. Environmental impact (Global Warming Potential and Water Footprint) and resource demand (Land Use and Non-renewable Energy Use) of raw materials (ingredients) used as matrices of meat substitutes; light dots – impact per kg of product in dry matter; dark dots – impact per kg of proteins; number in the brackets corresponds to the number of data points (Ciani et al., 2021; Delft et al., 2012; Deprá et al., 2020; Järviö et al., 2021; Mattick et al., 2015; Poore and Nemecek, 2018; Sandmann et al., 2021; Smetana et al., 2017, 2015; S. Smetana et al., 2021; Tuomisto, 2019; Upcraft et al., 2021)

farmed fish and are mostly associated with the fuel use during fishing (Avadí et al., 2020). However, if the impact of bottom trawling is considered, then the impact increases dramatically due to the increased demand for energy (Sala et al., 2022) and impact on habitat change (Sala et al., 2021).

Dairy-based texturized meat substitutes (e.g., “Valess”), while on the market, are poorly assessed in environmental studies. The LCA study of Smetana et al., the only relatively recent study with dairy-based meat substitute (Smetana et al., 2015), indicates the impact in the scope of 4.38-4.95 kg CO_2eq. kg^{-1} and 3.32-3.41 m^2 kg^{-1} $year^{-1}$, 48.8-59.1 MJ kg^{-1}, which corresponds well to older approximations of 3.8-6.3 kg CO_2eq. kg^{-1}, 2.9-3.8 m^2 kg^{-1} $year^{-1}$, 55.5 MJ kg^{-1} (Blonk et al., 2008; Head et al., 2011).

Application of alternative (underutilized) and wild animals to substitute conventional meat production, while being a source of important nutrients for local rural populations, is not completely justifiable in terms of environmental impact, resource availability, and biodiversity. On the other hand, the use of animal-derived components (e.g., milk) might be feasible, especially if it is considered as a secondary by-product.

3.3. *Cultured meat (product of cellular agriculture)*

Cultured meat production is still at the development stage and major uncertainties regarding the commercial scale production system still exists. Especially, the development of low-cost culture medium ingredients and energy efficient large-scale bioreactor systems are some of the key challenges (Post et al., 2020). Due to these uncertainties, the current estimates of the environmental impacts of cultured meat rely on modelling, assumptions, and data from laboratory-scale experiments. Some studies have estimated the impacts of future large-scale cultured meat production by using hypothetical process design (Smetana et al., 2015), whereas other studies are based on the currently commonly used cell-culturing systems (Delft et al., 2012; Mattick et al., 2015). Smetana et al. (Smetana et al., 2015) used the data from previous studies by Tuomisto and Teixeira de Mattos (Tuomisto and de Mattos, 2011) as the basis for their estimates, but assumed that cyanobacteria are produced in a bioreactor instead of an open pond. Due to the use of cyanobacteria as a main source of nutrients, these two studies had the lowest estimates for the land use of cultured meat (Fig. 2). However, the production of cyanobacteria in a bioreactor instead of an open pond increased the energy use and GHGE of cultured meat substantially. The current state of the art for the production of steak-like meat still relies on a vast list of growth factors and animal-based serums for the culturing process (Kang et al., 2021).

The LCA studies of cultured meat production in systems resampling the current mammalian cell culturing systems show that the production of the culture medium ingredients and the bioreactor energy use have the highest contribution to the environmental impact of the process (Delft et al., 2012; Mattick et al., 2015). Mattick et al. (Mattick et al., 2015) modelled the environmental impacts of cultured meat production in the US by using data for Chinese Hamster Ovarian (CHO) cells as a basis and assuming the use of serum-free culture medium consisting of synthetic amino acids, glucose, vitamins, minerals and soybean hydrolysate. The results showed higher GHGE for cultured meat than that of pork and poultry, but 75% lower emissions compared to beef. Cultured meat had lower land use than any of the livestock products. The eutrophication potential of cultured meat was lower than that of beef and pork, and at the same level with poultry.

The findings of a white paper reporting the results of a cultured meat LCA study based on data collected from start-up companies (Delft et al., 2012) were in line with (Mattick et al., 2015), but also showed that lower emissions compared to pork and poultry could be achieved by using low emission energy sources in cultured meat production. They also found that obtaining amino acids from plant-based hydrolysates instead of producing them synthetically could help reducing the environmental impacts of cultured meat.

Cultured meat (even though it is hypothetically modelled) is envisioned to require fewer resources than conventional meat. Optimization for cultured meat is envisioned through highly specialized, targeted tissue cultivation (no need for the resources of "peripheral systems"), higher production rates (the optimal cultivation system improving current 47% energy feed conversion efficiency and 72% protein feed conversion efficiency) and vertical system farming principles (Alexander et al., 2017; Rubio et al., 2020).

In general, the current evidence shows that cultured meat could have the potential to have lower environmental impacts compared to livestock products, and especially beef, if the production process could be scaled up in a cost-efficient way and if low-emission energy sources were used in the production. The highest benefits are due to lower land use requirements and GHGE. However, as the development of cultured meat technology is in its early stages, it is unlikely that the products will be widely available in the near future. Therefore, cultured meat should be regarded as a possible option in the longer term, but it will not provide a solution to the current urgent requirements for action that are needed to achieve the SDGs by 2030.

3.4. Single-cell proteins (microalgae and bacteria)

Microalgal biomass has been considered a source of various products of value such as saturated and polyunsaturated fatty acids, pigments, carbohydrates and in particular proteins (Caporgno and Mathys, 2018; Postma et al., 2017). Advantages of microalgal cultivation such as reduced use of arable land (Postma et al., 2017), use of waste streams as nutrient sources (Rashid et al., 2020), high productivity (Vadlamani et al., 2019) and control of algal biomass composition (Zarrinmehr et al., 2020) contributed to the increased interest in developing novel and green cultivation systems. However, the cultivation of microalgae in bioreactors may not necessarily exhibit environmental benefits. Culture conditions such as the cultivation system, location, season, scale, and algal species considered (Schade and Meier, 2019), as well as the source of nutrients, are considerably influencing the environmental impact (Smetana et al., 2017). Schade and Meier stated that "not every cultivation system is suitable for every specific climatic prerequisite and thus no system is favorable in general" (Schade and Meier, 2019). Because of the relatively low biomass concentrations achievable in photobioreactors, the phototrophic microalgae cultivation is usually done on a larger scale. For instance, Smetana et al. considered a scale of 580 L of an open raceway pond to produce 1 kg *Chlorella vulgaris* biomass sludge with a moisture content of 85-90% (w/w) (Smetana et al., 2017). Contrarily, the same amount of *C. vulgaris* biomass produced under heterotrophic conditions in the presence of glucose as a carbon source requires only a volume of 10 L. Similar results were found for *Galdieria sulphuraria* growing heterotrophically on hydrolyzed food waste (Thielemann et al., 2021). Generally, the smaller the volume, the less energy is needed for heating and the smaller is the environmental impact. In order to transform microalgal biomass into a sustainable and environmentally friendly source of proteins all separate process steps from nutrients and energy supply, cultivation, and biomass processing as well as protein extraction need to be analyzed and optimized. Deprá et al. investigated the environmental impact of *C. vulgaris* and *Arthrospira platensis* biomass production under different culture configurations (Deprá et al., 2020). The investigated process included cultivation in raceway pond and tubular photobioreactor, centrifugal harvesting and spray-drying. Irrespective of the strain used, more than 70% of the energy (334.8 kWh for *C. vulgaris* and 249.8 kWh for *A. platensis*) was needed for the dewatering and drying of the biomass produced in the raceway pond. Contrarily, the energy demand of the tubular photobioreactor was considerably higher, and around 80% (549.1 kWh) of the energy was needed alone for cultivation. The production of 1 kg dry *C. vulgaris* biomass produced in the tubular photobioreactor and raceway pond was 220.3 and 141.3 kg CO_2eq., respectively. The production of *A. platensis* in the raceway pond resulted in 100.9 kg CO_2eq. The second largest contribution to the environmental impact comes from the applied nutrients (N and P). For instance, Herrera et al. have shown that nutrient management is critical to the sustainable production of microalgae and that the nutrients associated GHGE can be reduced by 80% and 20%, respectively, when nutrients from slurry and wastewater are recovered and recycled (Herrera et al., 2021).

Microalgae are not the only source of single-cell protein. In the recent years, the utilization of urban waste has been investigated to produce a wide range of microbes rich in proteins. Molitor et al. investigated a system where *Clostridium ljungdahli* first converted CO_2 into acetate under strict anaerobic conditions, coupled with a conversion of acetate and a nitrogen compound under aerobic conditions into *Saccharomyces cerevisiae* biomass (Molitor et al., 2019). The authors achieved a high protein productivity in cultured media of around 1-2 g protein L^{-1} day^{-1} using *S. cerevisiae*. An analysis of the environmental impact is currently missing. Similar to the production of microalgal biomass, the environmental impact depends on culture conditions and, in particular, on the source of nutrients. The nitrogen needed for this approach may come from food waste and the environmental impact associated with nutrient formation might be skipped. Another approach to single-cell protein production that has evolved in the last years is "power-to-protein". Power-to-protein means that a hydrogen-oxidizing bacteria is cultured in a bioreactor where continuously hydrogen is generated by water electrolysis. The hydrogen oxidizing bacteria use the formed H_2, O_2 and CO_2 to form a protein-rich biomass. The environmental impact of energy sources used for the cultivation of hydrogen oxidizing bacteria to a large extent defines the sustainability of such biomass. For example, GHGE of such biomass could vary in the range of 1.05 – 8.4 kg CO_2eq. kg^{-1} of dried product, which in combination with other impacts is 53-100% lower than animal-based protein sources (Järviö et al., 2021). It has also been shown by Putri et al. that urban organic waste can be utilized as a nitrogen source in this approach (Putri et al., 2019). Sillman et al. carried out a LCA to analyze environmental sustainability (Sillman et al., 2020). In their LCA, they examine production as a nitrogen source, CO_2 sources, electricity generation, bioreactors with *in situ* and external electrolysis, post-processes for biomass cultivation, and water removal. The GHGE impact was found in the best case to be around 1.7 kg CO_2eq.

and in the worst case to be around 4.7 kg CO_2eq. kg^{-1} protein. The authors found out that the major effect on the environmental impact comes from the generation of electricity. Particularly, the electrolysis of water is energy intensive, and the source and technology must be carefully chosen to minimize the environmental impact. An option is to focus on external water electrolysis instead of *in situ*.

Generally, the environmental impact of single-cell proteins is dependent on the use of renewable energy. The greater the use of renewable energy in processes, the better the environmental performance. However, the time required to produce a certain amount of biomass and, eventually, proteins must be taken into account. Deprá et al. stated a biomass productivity of 0.2 and 0.32 g L^{-1} and day for *C. vulgaris* and *A. platensis*, respectively, grown under phototrophic conditions in raceway ponds (75). This could result in a protein production of 0.1 and 0.16 g L^{-1} and day, respectively. As previously stated Molitor et al. reported a protein production of 1-2 g per L and day in their *C. ljungdahli* / S. *cerevisiae* system (Rashid et al., 2020). The discovered productivities appear to be too low to allow a production at industrial scale, and thus more research is required to allow for more efficient production in the future.

3.5. Mycoprotein meat substitutes

Fungi biomass processing has a significant impact in addition to the impact of raw biomass production. According to Jungblunth et al., (Jungbluth et al., 2016) the processing and distribution of mycoprotein products doubles the environmental impact, especially the carbon footprint (from 2.44 to 4.99 kg CO_2eq. per portion). Similar or even higher rates of impact are found in earlier studies. Study of (Smetana et al., 2018, 2015) also indicated similar rates of impacts 5.55-6.15 kg CO_2eq. kg^{-1} and 60.07-76.8 MJ kg^{-1}. A recent study relying on production modelling approaches defined the impact of 1 kg of protein (L-Mycoprotein) in the scope of 23.66 kg CO_2eq., 4.4 m^2 arable land and 2.2 m^3 water consumed (Upcraft et al., 2021).

Despite the availability of fungi and mycoprotein products on the market, there is a clear lack of studies and production data in this domain. Preliminary studies indicate that the production of mycoprotein requires a lot of energy and high-quality raw materials (e.g., sugar), which results in high GHGE and energy use impacts.

3.6. Insect-based alternatives and hybrid products

There are only a few studies dealing with the LCA of insect-based meat substitutes. They can be grouped into those assuming that "fresh" insect biomass is an equivalent for raw meat, and those assessing more advanced processed products imitating meat texture. The first group of studies, dealing mostly with insect species allowed for food (e.g., mealworms: *Tenebrio molitor*, crickets: *Acheta domesticus*, and grasshoppers) define the environmental impact of raw insect biomass in the scope of 3.9-29 kg CO_2eq. kg^{-1} proteins (Upcraft et al., 2021). When more processed products are considered (e.g., burgers, schnitzel-like meat substitutes), then the impacts of insect production combine with the impacts of associated ingredients (e.g., plant flours or proteins, fibers, spices, and even meats), thus becoming hybrid products.

The percentage of the meat successfully replaced by insects is different depending on the type of insects but also on the type of product or processing: up to 40% of pork myofibrillar protein could be replaced with *T. molitor* protein in meat emulsion systems (Kim et al., 2020). Specifically, for *T. molitor* larvae, as well as for *Bombyx mori* pupae, it is indicated that defatted flour can be suitable for manufacturing emulsion sausages without adverse effects on technological or nutritional properties (Kim et al., 2016). It was found that hybrid sausages had higher acceptability than burgers. For example, it was possible to formulate frankfurters with a combination of 40% pork meat and 10% yellow mealworm (Choi et al., 2017). More interesting is the application of fat extraction and protein purification methods to separate insect protein fractions (*T. molitor*) and use the protein concentrates and isolates as targeted ingredients. The GHGE impact of such protein fractions ranges from 3.05 to 10.87 kg CO_2eq. kg^{-1} protein extract (Laroche et al., 2022).

All these hybrid meat products have the potential to bridge the gap between meat and meatless products, as it has been reported that no significant difference in acceptability could be perceived (Neville et al., 2017; Profeta et al., 2020). The same strategy may apply to overcome food neophobia, as, for example, insects as novel ingredients were shown to be easier to introduce into diets when incorporated into familiar ready-to-eat food preparations (Caparros Megido et al., 2016). Impacts of plant-meat hybrids range in the scope of 23.24-26.73 kg CO_2eq. kg^{-1} proteins for GHGE; 180-232.4 MJ kg^{-1} proteins for non-renewable energy use (NRE); 23.2-26.7 m^2a kg^{-1} proteins for land use (LU) (Baune et al., 2021), while the impacts of insect-plant and mycoprotein-plant hybrids range in the scope of 5.24-7.14 kg CO_2eq. kg^{-1} proteins for GHGE; 46.74-83.8 MJ kg^{-1} proteins for NRE; 5.9-18.56 m^2a kg^{-1} proteins for LU (Sergiy Smetana et al., 2021).

Insect biomass, therefore, could be perceived as a viable ingredient in a meat analog matrix; however, the processing functionality of insect proteins is limited, and therefore it should be combined with plant biomass for efficient fiber texture formation. It should be perceived as an example of plant-insect hybrid products, which, compared to plant-animal hybrid products, are more environmentally beneficial and can be recommended for further exploration.

4. Comparative analysis of conventional and alternative protein sources impacts on environment

Plant-based foods in the human diet have twice as low GHGE (4,963 TgCO_2eq.) as animal-based foods (9,923 TgCO_2eq.) (Xu et al., 2021). Furthermore, literature analysis reveals that on a protein basis, animal-based proteins have a considerably higher GHGE than proteins incorporated in plant-based meat substitutes: farmed fish (34%); poultry meat (43%), pig meat (63%), farmed crustaceans (72%), beef from dairy herds (87%), and beef from beef herds (93%). Therefore, it can be tempting to conclude that all plant-based proteins always lower the environmental impact of the meat substitutes as compared to different types of meat. However, processed plant-based meat substitutes have 1.6-7 times higher environmental impact than less processed plant protein sources (e.g., tofu, pulses, and peas) (Santo et al., 2020). Detzel et al. in their research conducted in the scope of the Protein2Food project, identified that extruded plant-based meat substitutes in certain conditions could have a carbon footprint very similar to that of chicken meat, and in terms of resource demand (land, energy, and water), it could be even higher (Detzel et al., 2021). The analysis of the recent literature confirmed such outcomes for most impact categories. Impacts of both animal and plant-based ingredients can vary widely, and there is a range in which results of impact assessment overlap, so it is difficult to set a base case that would be used for comparison in all cases (Fig. 2). Beef is typically considered a product with a high environmental impact, higher than most meat substitute ingredients. Still, for some protein sources like microalgae, the analysis shows that, based on a weight basis, the GHGE and NRE demand of microalgae can be much higher than those of beef and other plant raw materials. When used as meat substitute ingredients, cell-based cultures and insects also tend to have greater environmental impact. On the basis of protein comparisons, it was identified that for most categories (except for water footprint) the range from most impactful to least impactful can be drawn: beef, microalgae, cell meat, poultry meat, insects, plants. Water footprint is not indicative, with results being different in a few orders, which could relate to the application of different assessment methodologies.

The incorporation of raw materials into ready-to-consume products shifts the relative impacts of meat substitutes. Plant-based extrudates (intermediate products) demonstrate low GHGE: 7.7-7.9 kg CO_2eq. kg^{-1} having impact in lower range compared to chicken meat protein 7.7-11.3 kg CO_2eq. kg^{-1} (Detzel et al., 2021). Plant-based meat substitutes

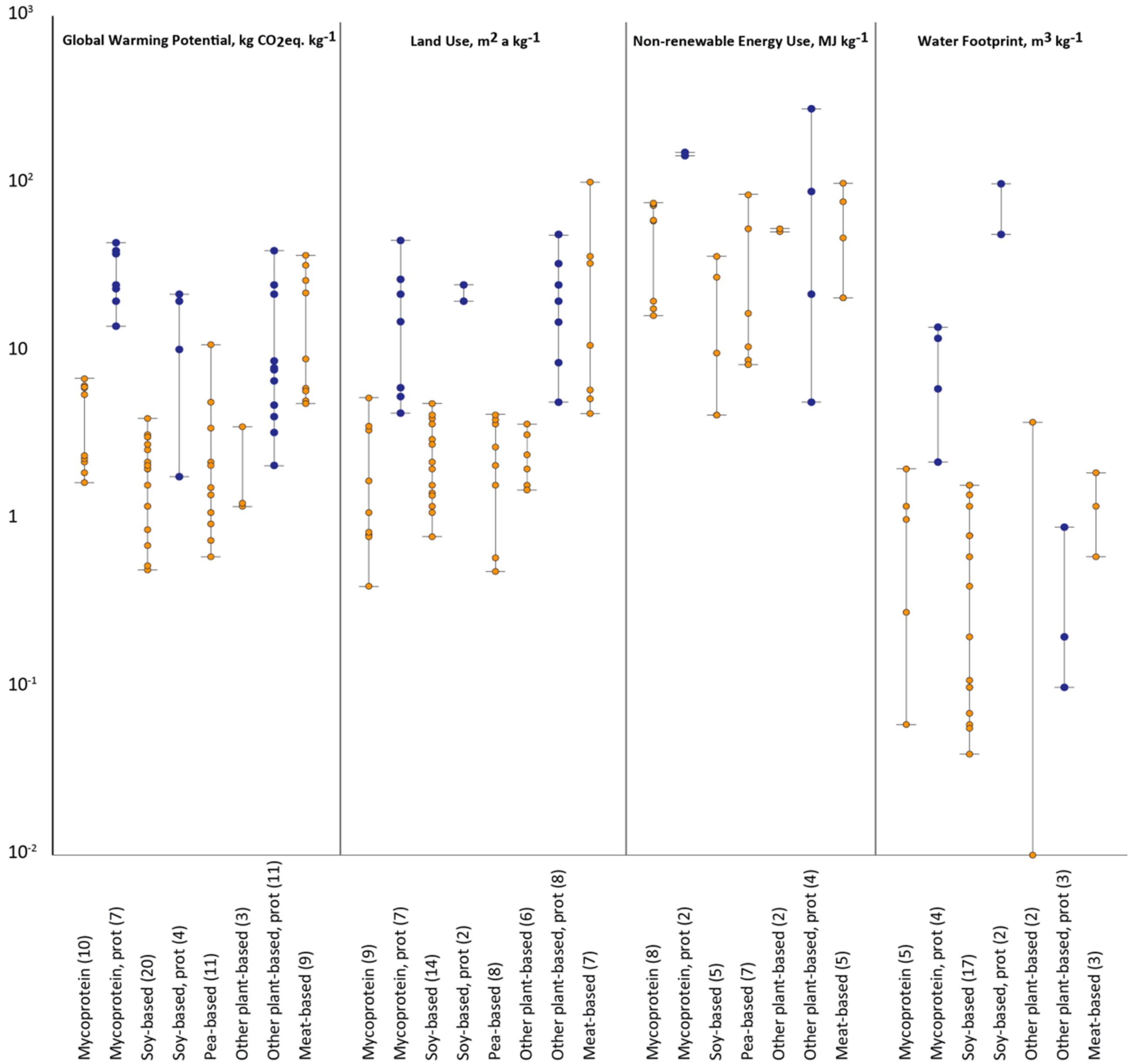

Fig. 3. Environmental impact (Global Warming Potential and Water Footprint) and resource demand (Land Use and Non-Renewable Energy Use) of meat and meat substitute products; light dots – impact per kg of product in dry matter; dark dots – impact per kg of proteins; number in the brackets corresponds to the number of data points (Ciani et al., 2021; Delft et al., 2012; Deprá et al., 2020; Järviö et al., 2021; Mattick et al., 2015; Poore and Nemecek, 2018; Sandmann et al., 2021; Smetana et al., 2017, 2015; S. Smetana et al., 2021; Tuomisto, 2019; Upcraft et al., 2021)

at the same time are significantly lower in GHG footprint (2-22.35 kg CO_2eq. kg^{-1} protein) (Detzel et al., 2021; Mejia et al., 2018; Saget et al., 2021) than hypothetical cultured meat (average 56 kg CO_2eq kg^{-1} protein) (Santo et al., 2020), however cultured meat has a potential to have lower impact than beef and farmed crustaceans (Poore and Nemecek, 2018). Accounting for the land use change impact can increase the impact of chicken meat to 26.7-46.7 kg CO_2eq for 1 kg of proteins (Detzel et al., 2018). Similarly, a few-fold improvement potential was observed in several categories (terrestrial eutrophication, acidification, photochemical oxidant formation, particulate matter, ozone depletion) for plant fiber products compared to chicken meat. However, in categories of cumulative energy demand, blue water consumption, aquatic eutrophication, and land use – no statistical differences were observed (Detzel et al., 2018).

Pea-based meatballs are demonstrated to be more environment beneficial on a weight basis (cooked product) and with the inclusion of nutritional properties in the comparative (functional) unit in all the impacting categories compared to beef meatballs (Saget et al., 2021). The difference in environmental impact was at least two times lower for pea meatballs (for both weight and nutritional functional units) (Fig. 3).

Meat-based foods had a higher environmental impact in terms of GHGE and land use than most products, with only a few cases falling in the upper impact ranges of mycoproteins and pea-based foods (Fig. 3). Such differences are not that obvious when NRE and water footprints are compared. For the last two categories, mycoprotein and plant-based meat substitutes could have a higher impact than meat products on a kg basis. It is necessary to indicate that the meat-based category included pork and poultry impacts.

The analysis of the impacts of meat substitutes on a protein basis did not define the significant difference between plant- and mycoprotein-based products in all categories. It was not possible to draw conclusions due to the limited data available in some categories (NRE and

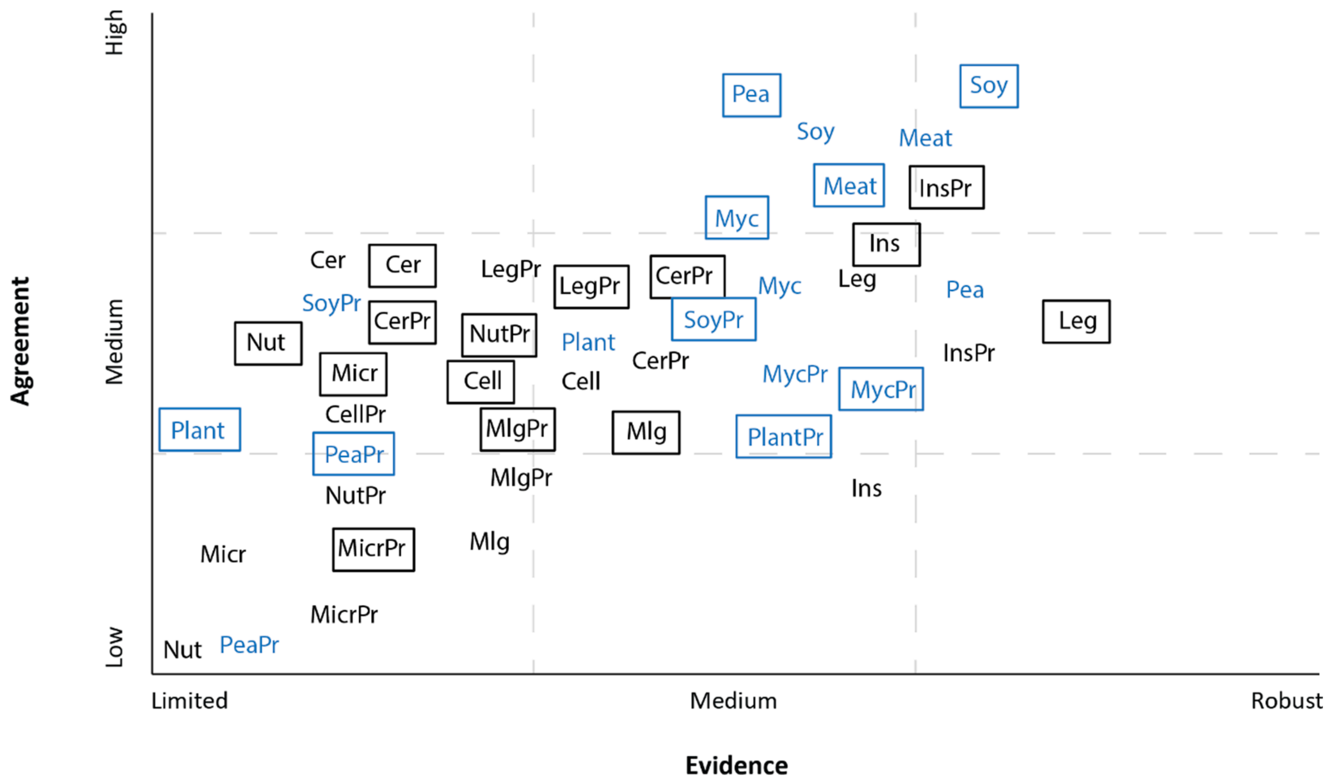

Fig. 4. Data availability on environmental impact and resource demand of meat substitutes; framed words represent environmental impacts; non-frames resource demands; in black letters – raw materials; in blue letters – incorporated in developed products; Pr prefix – values for protein basis; Cell – cell-based meat; Cer – cereals; Ins – insects; Leg – legumes; Meat – meats; Micr – microbial; Mlg – microalgae; Myc – mycoprotein; Nut – nuts; Pea – pea; Plant – plants; Soy – soy (composed after (Mastrandrea et al., 2010)

water footprint). The availability of comparable data on the meat substitutes, which are often based on alternative and novel proteins (cultured meat), is quite limited. While some sources are well covered (Fig. 4), such sources as microbial protein, cell meat, pea protein, nuts and microalgae are not well covered, and the spread of data for such sources is of low agreement.

5. Recommendations for further research

Meat analogs (substitutes) are the products of the co-evolution of consumer demand and processing technologies. Among the alternative proteins, meat analogs are among the most advanced products, relying on decades of research and development for the successful recreation of meat texture, taste, and appearance (Grossmann and Weiss, 2021). Despite the extensive research and advances in processing technologies, there is a growing scope for the basic research associated with a wide range of alternative proteins coming on the market. While the environmental impacts of meat analogs are well documented for plant-based substitutes, they are frequently unknown or understudied for other sources (microalgae, mycoproteins, single-cell proteins, cultured meat). Further research covering a wide spectrum of data on the production and processing of alternative proteins, as well as any potential trade-offs between environmental, social and economic aspects, is urgently needed. Moreover, there is a need for holistic studies dealing with the clarification of potential trade-offs and synergies between the environmental impact and nutritional properties of meat substitutes. It is especially important because both aspects are not linearly dependent on each other. They also influence human health in direct (supply of nutrients and potential health risks) and indirect (impact on human health through the change of environmental properties) ways. Such complexities call for further studies dealing not only with characterization of environmental and health impacts of meat substitutes but also with relevant comparison with different animal-based products and meats.

Multiple food system analyses currently available (Brouwer et al., 2020) do not provide a reliable model for higher-level system modelling. Some studies successfully reflect on indirect environmental, economic, and social factors, as well as resource and environmental impact trade-offs. A further model, based on interaction between the actors of a complex food system and able to define the second and third order impacts (e.g., rebound effects), would be required to predict the influence and role of meat substitutes in future diets and potential shifts with the inclusion of other protein alternatives.

Declaration of Competing Interest

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

Data availability

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

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