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LCA FOR ENERGY SYSTEMS AND FOOD PRODUCTS

Meat alternatives: life cycle assessment of most known meat substitutes

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Abstract
Purpose Food production is among the highest human environmental impacting activities. Agriculture itself accounts for 70–85 % of the water footprint and 30 % of world greenhouse gas emissions (2.5 times more than global transport). Food production's projected increase in 70 % by 2050 highlights the importance of environmental impacts connected with meat production. The production of various meat substitutes (plant-based, mycoprotein-based, dairy-based, and animal-based substitutes) aims to reduce the environmental impact caused by livestock. This article outlined the comparative analysis of meat substitutes' environmental performance in order to estimate the most promising options.
Methods The study considered "cradle-to-plate" meal life cycle with the application of ReCiPe and IMPACT 2002+ methods. Inventory was based on literature and field data. Functional unit (FU) was 1 kg of a ready-to-eat meal at a consumer. The study evaluated alternative FU (the equivalent of 3.75 MJ energy content of fried chicken lean meat and 0.3 kg of digested dry matter protein content) as a part of sensitivity analysis.
Results and discussion Results showed the highest impacts for lab-grown meat and mycoprotein-based analogues (high demand for energy for medium cultivation), medium impacts for chicken (local feed), and dairy-based and gluten-based meat substitutes, and the lowest impact for insect-based and soy meal-based substitutes (by-products allocated). Alternative FU confirmed the worst performance of lab-grown and mycoprotein-based analogues. The best performing products were insect-based and soy meal-based substitutes and chicken. The other substitutes had medium level impacts. The results were very sensitive to the changes of FU. Midpoint impact category results were the same order of magnitude as a previously published work, although wide ranges of possible results and system boundaries made the comparison with literature data not reliable.
Conclusions and recommendations The results of the comparison were highly dependable on selected FU. Therefore, the proposed comparison with different integrative FU indicated the lowest impact of soy meal-based and insect-based substitutes (with given technology level development). Insect-based meat substitute has a potential to be more sustainable with the use of more advanced cultivation and processing techniques. The same is applicable to lab-grown meat and in a minor degree to gluten, dairy, and mycoprotein-based substitutes.

Keywords Insect meal · LCA · Meat substitute · Mycoprotein · Soy meal

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1 Introduction

Food production is among the biggest human environmental impacting activities. Agriculture itself is responsible for 70–85 % of water footprint and 30 % of world greenhouse gas (GHG) emissions (Shiklomanov 2003; Bellarby et al. 2008; Pfister et al. 2011; Hoekstra and Mekonnen 2012; Vermeulen et al. 2012; Garnett 2014; Pfister and Bayer 2014). Moreover, food demand is projected to increase by 70 % till 2050 (FAO

2009), which will result in associated impacts to increase as well. Meat production is the most impacting activity in food production (Steinfeld et al. 2006). At the same time, understanding environmental and economic costs of meat production led to the development of meat analogues and their successful introduction to market and production (Tijhuis et al. 2011). The most known and successful meat substitutes are based on plant material (soy, peas, lupine, rice, etc.), animal-produced proteins (milk, insects, lab grown), and mycoproteins.

Several studies indicated that meat substitutes had a lower environmental impact than meat (Håkansson et al. 2005; Nonhebel and Raats 2007; Raats 2007; Blonk et al. 2008; Finnigan et al. 2010; Head et al. 2011; Tuomisto and de Mattos 2011; Berardy 2012; Oonincx and de Boer 2012; Van Huis et al. 2013). However, limitations of transportation systems or regional production specifics, used in global supply chains, could increase environmental impacts for soy and milk products. Meanwhile, future processing technology improvement could be beneficial for meat analogues with early development stage (lab-grown meat, insect-based analogues). Even though some comparisons of meat substitutes' environmental performance were published (Head et al. 2011; Van Huis et al. 2013), the analyses did not include possible differentiation of functional unit in terms of energetic values and digestibility of meat substitutes. In most cases, they presented the functional unit as 1 kg of product (weight based and did not include variations of nutritional qualities).

This study aims to compare main types of meat substitutes with chicken as the most environmentally friendly meat (Williams et al. 2006b; Roy et al. 2009), considering supply chain from raw material extraction (cradle) to product use by consumer (plate). The functional unit (FU) in the main part of the study is presented as 1 kg ready for consumption product (fried meat or meat analogue). This way, we consider differentiations in production and processing of meat analogues. Complete nutritional profile of foods was not taken into account in the main study as the comparison of results with literature data was one of the objectives. At the same time, alternative FU were considered in the sensitivity analysis. They were based on energy content of the products (3.75 MJ) and protein digestibility (0.3 kg of digested proteins). Sensitivity analysis also included main result verification with alternative assessment methodology (IMPACT 2002+).

2 Methods

The study concentrates on the attributional Life Cycle Assessment (LCA) as the main approach, as it does not account for consequences in the surrounding market. We do not aim at the determination of environmental effects for a specific location but at an average global comparison of most common meat analogues. The difference in technology development levels was not considered in the study but discussed in the article. However, a sensitivity analysis (Section 4) includes variations of performed functions (FU). The calculations were performed via SimaPro 8 software with Ecoinvent 3 and LCA Food DK Databases (Nielsen et al. 2003; Weidema et al. 2013). The study follows ISO 14 040 and 14 044 standards (ISO 14040 2006; ISO 14044 2006) with an exception of external review, as the results of the study are not for specific products' environmental impact public disclosure. The conceptual comparison of main meat analogue types and the identification of the most promising substitutes for technologies improvement is the main goal of the study.

2.1 Products studied

The study concentrates on six meat analogues in comparison with the most environmentally efficient meat—(1) chicken (Williams et al. 2006b; Roy et al. 2009). From one side, the analysis included substitutes based on animal products: (2) dairy based, (3) lab grown, and (4) insect based. From the other side, the study investigated plant- and mycoprotein-based products: (5) gluten based, (6) soy meal based, and (7) mycoprotein based. In total, the study analyzes seven products (Table 1).

2.2 Environmental impacts considered

The characterization method (ReCiPe V1.08), used in the main study, is selected as the most integrative and recent one (Goedkoop et al. 2013a). Such approach allows overall single score product comparison, as well as detailed analysis with multiple characterization factors (climate change, ozone layer depletion, human toxicity, acidification, ecotoxicity, land occupation, metal and fossil fuel depletion, etc.). This study includes multiple effects for integrated impact visualization (eco-points). Another integrated methodology (IMPACT 2002+), which includes IMPACT 2002, Eco-indicator 99, CML, and IPCC methods, was used for the sensitivity analysis to indicate the reliability of the main study comparison results (Goedkoop and Spriensma 2001; Guinée et al. 2002; Pennington et al. 2005; IPCC 2007; Goedkoop et al. 2013b). Land use change (LUC) is an important environmental aspect of food and feed products, but its estimation and calculation do not follow a single standardized approach (Muñoz et al. 2013). This study included LUC analysis as a potential impact (due to the different levels of technologies development) in the discussion section (see Section 4.4). For calculating LUC, associated with various crops and agricultural products, we used an approach from Milà i Canals et al. (2012) with global land use data from FAOSTAT (FAO 2014). Greenhouse gas emissions associated with LUC were indicated according to published works (BSI 2008; Flynn et al. 2012).

Table 1 Main inputs in the production of meals used in the study (from cradle to plate)

Product	Resources used per FU (1 kg of ready-to-eat product)				
	Main ingredients	Electricity, MJ[d,g]	Tap water, kg[d]	Transport, kgkm[d,h]	Other[p]
(1) Chicken	1 kg chicken[a]	49.78*	16.3*	850*	–
(2) Dairy based[k]	6 kg skimmed milk[b]	12.27*	4.2*	360*	0.84 kg oat hull fiber[c]
(3) Lab grown[l]	1 kg urea[d]	103.5	420	110	–
(4) Insect based[m]	0.8 kg carrots[d]	10.762[f]	1.34[f]	128.5	0.57 kg grain mix (rye, wheat, barley)[d] 0.048 kg oat hull fiber[c]
(5) Gluten based[e]	1.622 kg wheat grain[d]	8.94	0.954	141.1	0.15 kg oat hull fiber[c]
(6) Soy meal based[n]	0.27 kg soy meal[d]	10.002[f]	0.73[f]	2791*	0.15 kg oat hull fiber[c]
(7) Mycoprotein based[o]	3 kg molasses from sugar beet[d]	21.32	40	215.45	0.069 kg nitrogen fertilizer[d] 0.04 kg egg white

[a] From a supermarket (LCA Food DK), based on live chicken for slaughterhouse (Ecoinvent 3 database)

[b] From dairy (LCA Food DK), water, electricity, and heat inputs are changed (Ecoinvent 3 database)

[c] By-product of oat cereals production, includes 2.3 m^2 of arable land occupation, use of 0.023 kg of nitrogen, 0.0048 kg of phosphate, and 0.0143 kg of potassium fertilizers, and 0.95 MJ of energy for 1 kg production (LCA Food DK, and Ecoinvent 3 database)

[d] Based on a product from Ecoinvent 3 database

[e] van Zeist et al. (2012) and Deng et al. (2013)

[f] Data from DIL e.V. are included

[g] Foster et al. (2006)

[h] Assumed resources transported 50 km to assembly and supermarket, 10 km from a supermarket to the consumer (McEachern and Warnaby 2006)

[i] Assumed, 20 g of oil needed to fry 0.5 kg of product

[j] PYR Ltd (2014)

[k] Berlin (2002), Blonk et al. (2008), and Head et al. (2011)

[l] Tuomisto and De Mattos (2010) and Tuomisto and Roy (2012)

[m] Oonincx and de Boer (2012) and Van Huis et al. (2013)

[n] Berk (1992) and Dalgaard et al. (2008)

[o] Raats (2007) and Finnigan et al. (2010)

[p] Table 1 does not include the data similar for all scenarios

2.3 Functional unit

This study focuses on the final product with a weight of 1 kg ready for consumption after assembly, processing, delivering, and frying at a consumer. The use of the final product weight was a basis for consumption comparability. Moreover, the selection of 1 kg weight unit was connected with the ability to compare results with those available in the literature. Therefore, the FU in the main part of the study is the satisfaction of a consumer with 1 kg protein-enriched product ready for the consumption.

The study included the comparison of results with alternative FU, which are based on calorific energy content (3.75 MJ) of ready for consumption product. This unit was identified as the basic integrative unit, which reflects the function of supplying high-quality protein meal with equal energy content. The use of products' energy content to compare their function is the basis for such assumption (Schau and Fet 2008). The choice of such approach resulted in the differentiations of the final product weight: 0.3 kg for chicken and lab-grown meat, 0.4 kg for dairy-based, 0.9 kg for insect-based, 0.375 kg for gluten-based, 1 kg for soy meal-based, and 0.94 kg for mycoprotein-based meals.

The other alternative FU included in sensitivity analysis of the study is connected with the function of meat products to supply the consumer with proteins, as meat is known to be the biggest protein source for human consumption. From this point, the digestible bulk protein content was considered as a basis for alternative FU. It was determined as 0.3 kg of the protein product (dry weight) corrected via Protein Digestibility Corrected Amino Acid Score (PDCAAS). PDCAAS for chicken is 1.00, dairy proteins—1.00, lab-grown meat (beef source)—0.92, insect proteins—0.86, wheat proteins—0.40, soy proteins—1.00, and mycoprotein—0.99 (Hoffman and Falvo 2004; Longvah et al. 2011). The protein content in the final product (wet content) is 31 % for chicken, 12.5 % for dairy-based meat substitute, 26 % for lab-grown beef, 13.5 % for insect-based meat substitute, 22.5 % for wheat protein content, 16.5 % for soy meal, and 10 % for mycoprotein (Van Huis et al. 2013; USDA 2014). Therefore, PDCAAS-corrected weight to get

0.3 kg of digestible protein content (alternative FU) would require 0.97 kg of chicken meat, 2.4 kg of dairy-based, 1.25 kg of lab-grown, 2.6 kg of insect-based, 3.33 kg of wheat protein-based, 1.82 kg of soy meal-based, and 3.03 kg of mycoprotein-based meat substitutes.

2.4 System boundaries

The paper relies on a single system boundary, drawn for meat substitutes and chicken (Fig. 1). However, the raw resources, assembly, recipes, and processing are different. The system is considered from cradle (raw resources production) to plate (consumer use). Recycling of packaging and waste treatment after human consumption is not in the scope of the study. The starting point for the system includes production of raw materials for the assembly of the food: protein feed growing for chicken (1) and dairy cows (2); crops growing for gluten (5), soybeans (6), and insect feed (4); medium growing for mycomycelium (7); and cyanobacteria growing and harvesting (3). The assembly and processing stage include chicken feeding and slaughtering (1); cows feeding, milking, and cheese-like processing with plant fibers (2); meat growing in cyanobacteria-based medium (e.g., cyanobacteria hydrolysate) with growth factors induced with *Escherichia coli* bacteria and vitamins (3); insect feeding, harvesting, drying, and processing with plant fibers (4); wheat grain processing into flour and gluten with texturized product forming (5); soy oil extraction and soy meal high-moisture extrusion (6); and mycomycelium growing, harvesting, and fermentation (7). The assembly stage includes transportation to a supermarket, cooling on a cooling counter, and additional product application (vegetable oil, salt). The final life cycle stage in this study includes transportation to the consumer (assumed 10 km) and frying on the electrical stove.

2.5 Data and sources

The LCA relies on data collected from multiple sources. It uses Ecoinvent 3 and LCA Food DK databases to identify the impact of raw materials growing and harvesting (Nielsen et al. 2003; Weidema et al. 2013); published data on meat substitute production, processing, and environmental impact (Berk 1992; Berlin 2002; Raats 2007; Blonk et al. 2008; Dalgaard et al. 2008; Finnigan et al. 2010; Tuomisto and De Mattos 2010; Head et al. 2011; Tuomisto and de Mattos 2011; van Zeist et al. 2012; Oonincx and de Boer 2012; Van Huis et al. 2013; Deng et al. 2013); and primary data of high-moisture extrusion processes (Table 1) from the German Institute of Food Technologies (DIL e.V.). The same global average databases, aimed for allocation, are used for the comparison analysis. Sensitivity analysis, included in the study, represents alternative functional units and methodology.

2.6 Allocation

Our study considered a few meat substitutes, produced along with other co-products. Some of the meat substitutes were by-products of bio-fuel production (6), butter production (2), or produced together with other products such as wheat starch (5). Option for minced meat production (from dairy cows) is not included in the scope. Literature indicated that lab-grown meat production is aimed at a single product, whereas mycoprotein-based analogue production and insect harvesting often included side stream use from other food productions, such as carrot peelings or molasses from sugar beets (Raats 2007; Oonincx and de Boer 2012; Van Huis et al. 2013). In our analysis, insect feeding used carrots and grain mixture (Oonincx and de Boer 2012), not by-products. As the main study FU has a weight-based origin, we used weight allocation for many processes in the analysis of meat analogues and meat. Lab-grown meat substitute (3) production required specific cyanobacteria production solely for the purpose of meat-growing medium, and so, no by-products were considered in the allocation. We did not include the waste treatment of the final product in the paper.

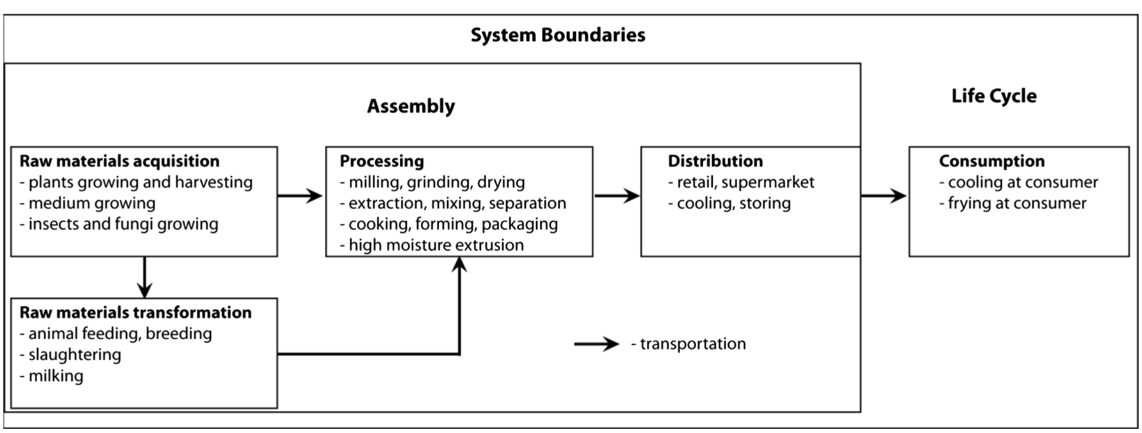


Fig. 1 Generalized system boundaries of the study

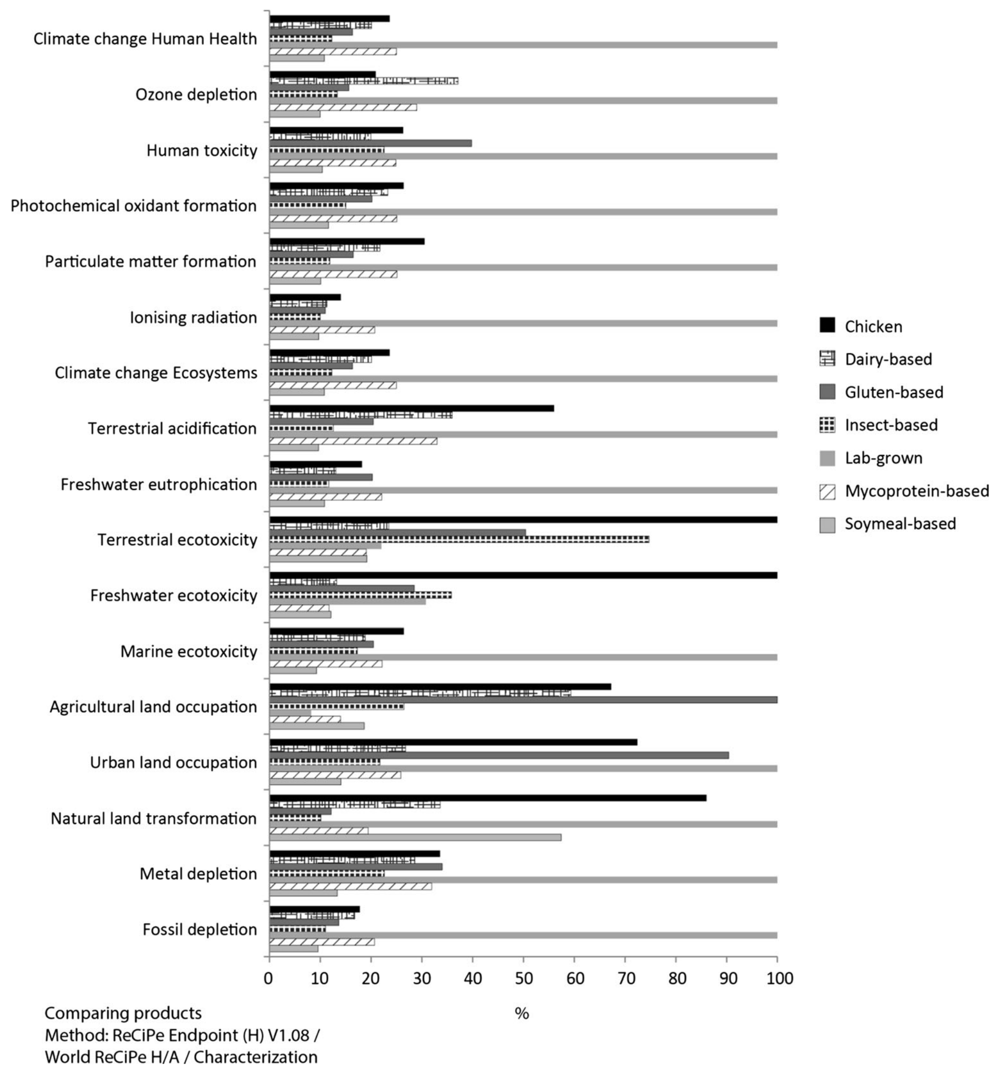
3 Results

There were large differences in environmental impacts between meat substitutes at midpoint impact categories of the studied life cycle "from-cradle-to-plate" (Fig. 2). The lab-grown meat had the highest impacts in most categories, except for agricultural land occupation (gluten based had the highest impact) and terrestrial and freshwater ecotoxicity (chicken meat was leading). Chicken meat also had high relative impacts in most midpoint categories. Gluten production was influential in metal depletion, human, and terrestrial toxicity. Insect-based meal showed high impacts in categories of terrestrial and freshwater ecotoxicity. Dairy-based substitute impacted high in categories of ozone layer depletion, terrestrial acidification, and agricultural land occupation.

Such differentiation could be explained with the high energy consumption by cyanobacteria medium growth for meat cultivation (3) and high environmental impacts in most categories associated with energy production. At the same time, the highest agricultural land occupation was assigned for gluten production (5), which required extensive land resources for wheat grain production. Use of grains and protein feed for chicken (1) caused the high impacts in ecotoxicity categories.

Lab-grown meat (3) was also responsible for the highest impact (Fig. 3) in endpoint damage assessment categories of human health (1.49 Pt), resources availability (0.967 Pt), and ecosystem quality (0.09 Pt). As stated previously, lab-grown meat production required a lot of energy, which caused the highest impact on the environment. The lowest impact in all endpoint categories was noted for insect-based (4) and soy meal-based (6) meat substitutes. The second highest impact on human health was assigned for chicken meat (0.383 Pt) and mycoprotein-based meal (0.372 Pt). Resources availability was also affected by dairy-based, chicken, and mycoprotein-based meals (0.17–0.2 Pt). Chicken (1), gluten-based (5), and dairy-based (2) meals affected ecosystem resources at medium levels (0.05–0.06 Pt).

Fig. 2 Product comparison midpoint characterization factors (from cradle to plate)



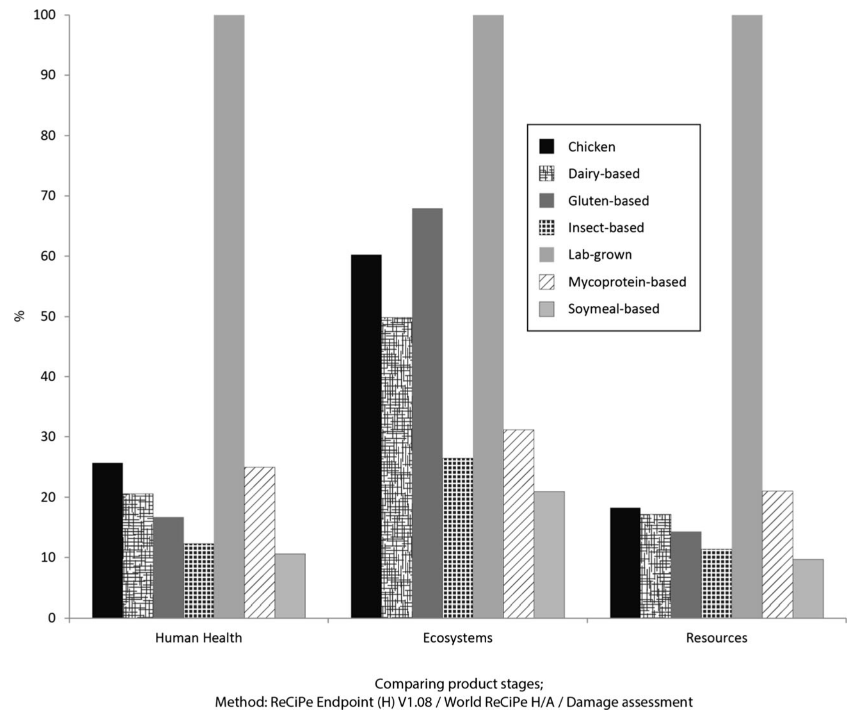


Fig. 3 Product comparison endpoint characterization factors (from cradle to plate)

The comparison of overall environmental impact (eco-points) showed the highest impact caused by the lab-grown meat (2.55 Pt). It had the highest impact in endpoint categories caused by the respiration inorganic emissions, climate changes, and non-renewable energy consumption (Fig. 4). Mycoprotein-based meat analogue and chicken were the second highest impacting products among compared. Their overall impact was 0.60–0.62 Pt. The lowest environmental impact was assigned for insect-based (4) and soy meal-based (6) meat substitutes (0.27–0.32 Pt). Gluten-based and dairy-based substitutes had higher impacts (0.45–0.52 Pt).

The biggest impact of the chicken meal (1) was associated with energy protein crops growing for chicken feed (37 %). Chicken growing added 25 % of the impact and slaughtering 2 %. Transportation was responsible for 8 % of impacts distributed along the whole supply chain. Frying at the consumer on the electrical stove was responsible for 26 % or 0.156 Pt (similar for all the products).

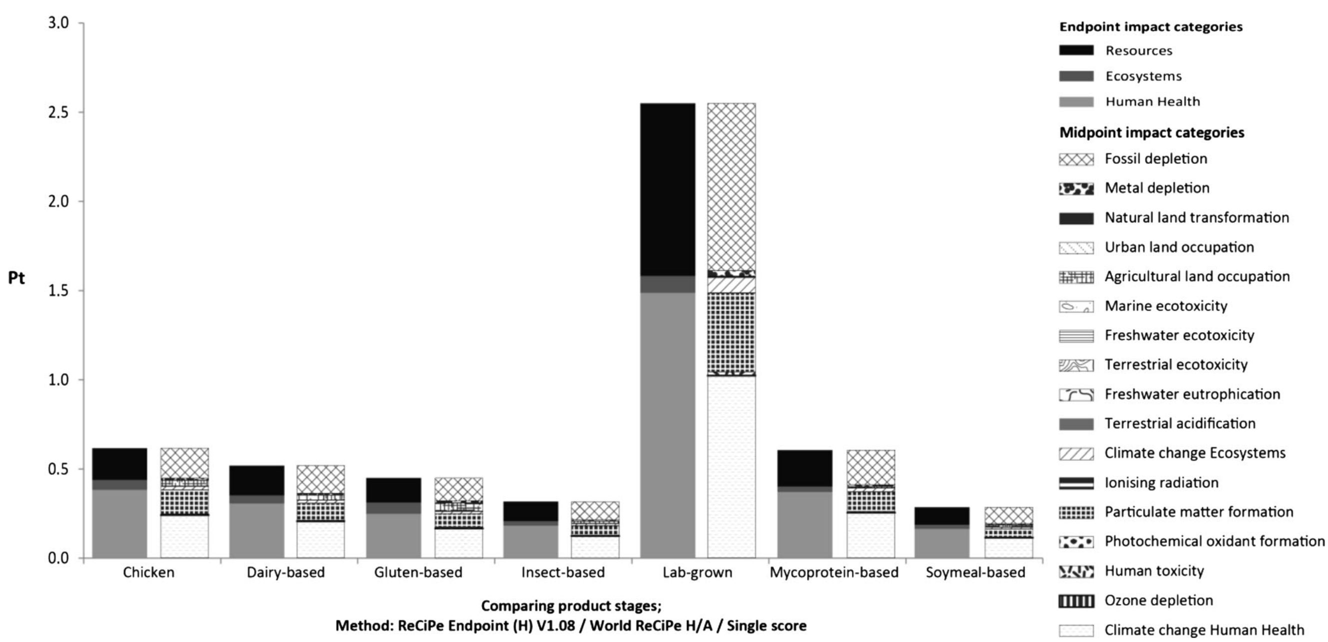


Fig. 4 Single-score product comparison FU 1 kg of ready to use product (from cradle to plate)

Other components and additives had a cumulative impact of 2 %.

Dairy-based meal (2) had a more diverse contribution impacts. The biggest impact came from energy used for frying at the consumer (30 %) and processing and refrigeration (10 %). The main ingredient acquisition also affected the system considerably—35 % of overall impact were caused by production of egg protein (17 %), oat hull fiber (10 %), and skimmed milk (8 %). Higher diversity of ingredients with relatively high mass caused the high impact of transportation (16 %). Other components and additives have a cumulative impact of 9 % (Fig. 5).

Lab-grown meat (3) affected the environment essentially due to the energy consumption used for the medium cultivation and meat growing (75 %). Final product frying resulted in 6 % of the overall impact. The urea used for cyanobacteria cultivation had an impact of 16 %. Other ingredients and components of product life cycle were responsible for 3 % of the impact.

Impact distribution of insect production (4) was associated with two main factors: energy use for frying (50 %) and for processing (5 %), and main feeding ingredients: cereal mix (15 %) and carrots (13 %). Transportation resulted in 10 % of the impact. Other factors were responsible for 7 % of the impact.

Impacts of gluten-based substitute components (5) were assigned similar to dairy-based analogue. The highest impact was caused by energy use at consumer stage (36 %) and at product processing (13 %). Wheat growing and harvesting took around 40 % of the overall impact. Transportation and other ingredients were of minor importance (7 % for transportation and 4 % for others).

Energy used for frying (58 %) and processing (18 %) had the highest influence on the impact from soy meal-based substitute (6). Soy meal was a by-product of bioenergy production, which was responsible for 12 % of the impact. Transportation was responsible for 5 % of the overall impact. Other components accumulated 7 % of the impact.

The production of mycoprotein-based substitute (7) was associated with high energy demand (45 % of impact for processing and 25 % for frying at consumer), component production (10 % for egg protein and 11 % for nitrogen fertilizer), and transportation (8 %). Other components did not have a considerably high impact.

4 Discussion

As a part of the discussion, we performed a few sensitivity analyses to verify the variability of the results. A number of parameters were changed to identify changes in environmental impacts connected to the selection of functional unit or assessment methodologies.

4.1 Energy allocation (alternative FU equal to 3.75 MJ energetic value of final product)

The main comparison of meat and meat substitutes was based on the mass of the foods. Some authors could argue that it is not an essential basis for food comparison as the differences in nutritional value could be significant (Schau and Fet 2008; Roy et al. 2009). The basic function of food for people is energy supply required to maintain the organism functioning (however, it is not the only function). That is why this study considered an alternative FU (3.75 calorific energy value) to evaluate the possible impact variations when the comparison was based on basic aggregated nutritional function.

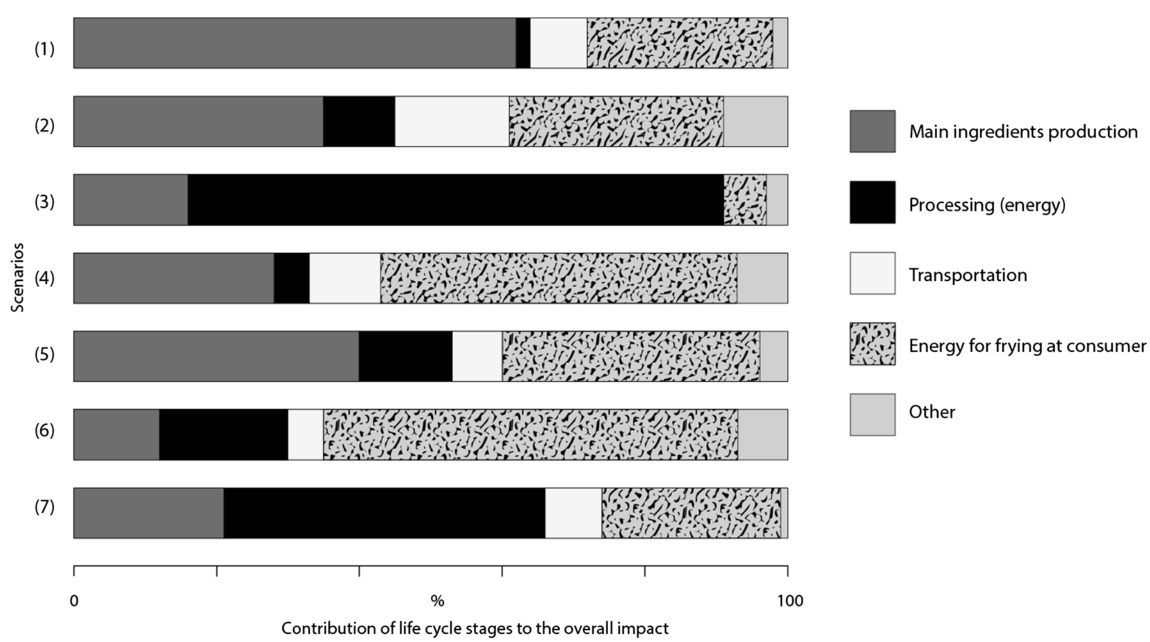


Fig. 5 Contribution of main life cycle stages to overall impact of the products (FU 1 kg)

Alternative analysis (with the same methods used, but alternative energy-based FU) indicated that lab-grown meat had the highest environmental impact (Fig. 6) similar to the main analysis (0.85 Pt). The second highest impact was noted for the mycoprotein-based meal (0.57 Pt). Dairy-based and gluten-based substitutes had the lowest impacts (~0.17 Pt). The chicken meat had 0.19 Pt. The other meat substitutes had medium environmental impacts without notable differences between them (~0.29 Pt).

4.2 PDCAAS corrected weight (alternative FU equal to 0.3 kg of digested proteins)

As energy calorific content is a simple, aggregated value, it does not reflect the full spectrum of nutritional values. In order to take a more nutritional aggregated approach, an alternative FU of 0.3 kg of digested proteins was considered. Results indicated (Fig. 7) that the lab-grown substitute had the highest impact (3.19 Pt). Mycoprotein-based and gluten-based meals shared second place (1.8 and 1.5 Pt), followed by dairy-based (1.2 Pt) and insect-based (0.8 Pt) substitutes. The lowest impacts were assigned after chicken (0.6 Pt) and soy-based meat (0.52 Pt).

4.3 IMPACT 2002+ methodology

Even though we applied recent integrated midpoint and endpoint impact methodology, the results could have been affected due to the selection of one methodology (Guinée et al. 2011). Therefore, results were checked for consistency with the application of IMPACT 2002+ methodology, which provides results for main midpoint impacts and aggregated data for endpoint categories. Main study FU (1 kg of ready-to-eat product) was tested.

With alternative analysis, results were distributed in similar to the main study order: lab-grown substitute had the highest impact (8.86 mPt); insect-based and soy meal-based substitutes had the lowest impact (1–1.2 mPt). Other meals had the medium impacts (1.9–2.2 mPt). Even though the integrated result distribution pattern is similar (Fig. 8), they cannot be compared to the results of the main study. But the midpoint results of the main categories are comparable (included in Table 2).

4.4 Comparison of LCA results with published data and their analysis

Most results of the study were the same order of magnitude as a previously published work. As the most published data reviewed the impacts at levels of midpoint impact categories, we performed the comparison based on main characterization results (Table 2). The results of main FU assessment with ReCiPe and IMPACT 2002+ methodologies were included in the comparison. The results highlighted higher impacts for climate change (lab-grown meat and gluten-based and mycoprotein-based meat analogues), land use (gluten-based

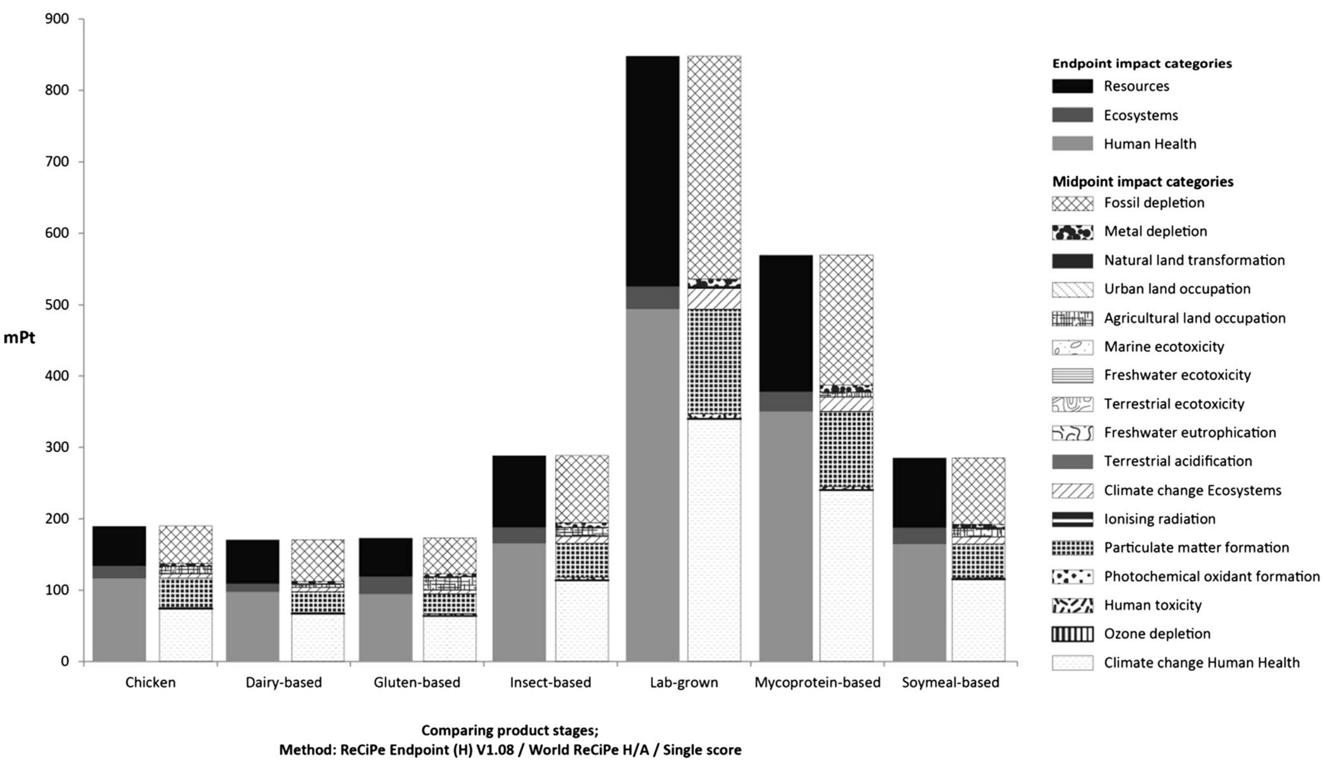


Fig. 6 Single-score alternative FU (3.75 MJ of food energy) product comparison (from cradle to plate)

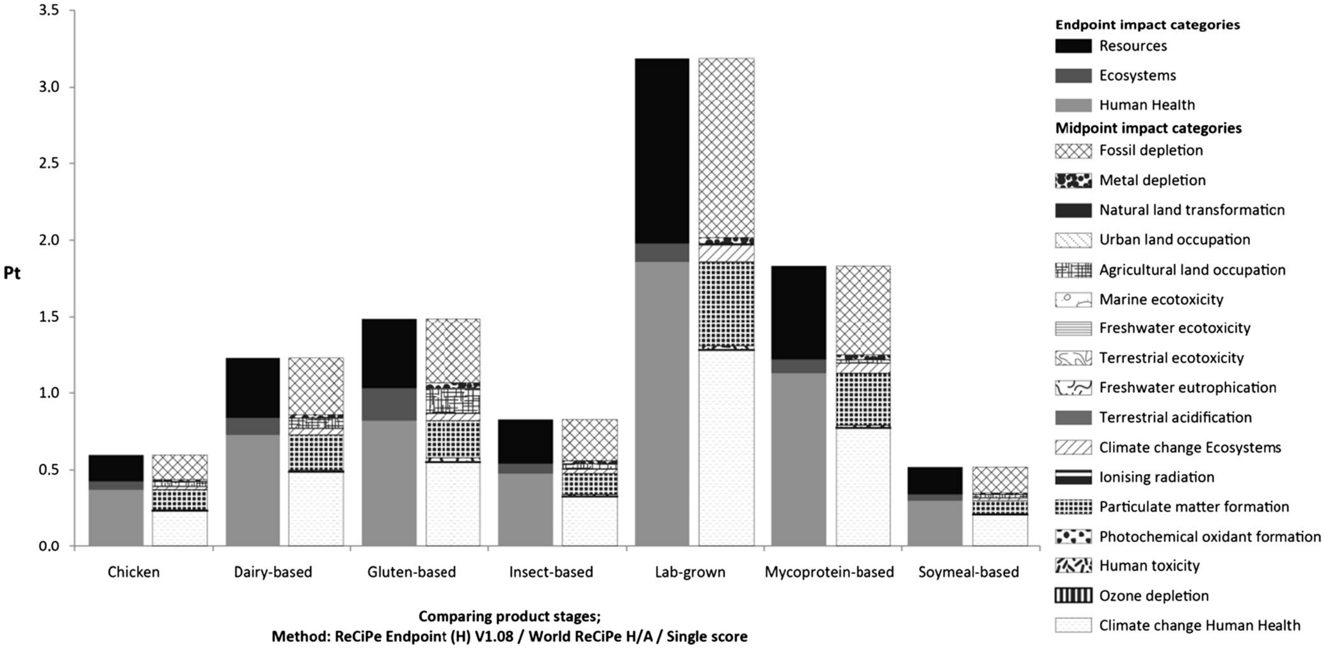


Fig. 7 Single-score alternative FU (0.3 kg of digested proteins) product comparison (from cradle to plate)

meat), and energy use (mycoprotein-based meat and chicken meat) comparing to available data in literature. Such differentiations could be explained with the inclusion of additional stages and resources (transportation, frying, and cooling at consumer) comparing to the other studies (Blonk et al. 2008; Tuomisto and de Mattos 2011; Tuomisto and Roy 2012; Deng et al. 2013), as results of contribution analysis indicated that frying at consumer was responsible for about 33 % of impact on average. It is accounted for the larger portion of environmental impacts for low-impacting meat substitutes (50 % for insect based and 58 % for soybean based) and for minor influence of highly impacting alternatives (6 % for lab-grown meat). The comparison of this study results with literature data was complicated due to the variations in system boundaries. This study relied on a product from cradle (feed or raw material production) to plate (cooking at the consumer). System boundaries of other studies were based on approaches from cradle to gate: as unprocessed weight at farm

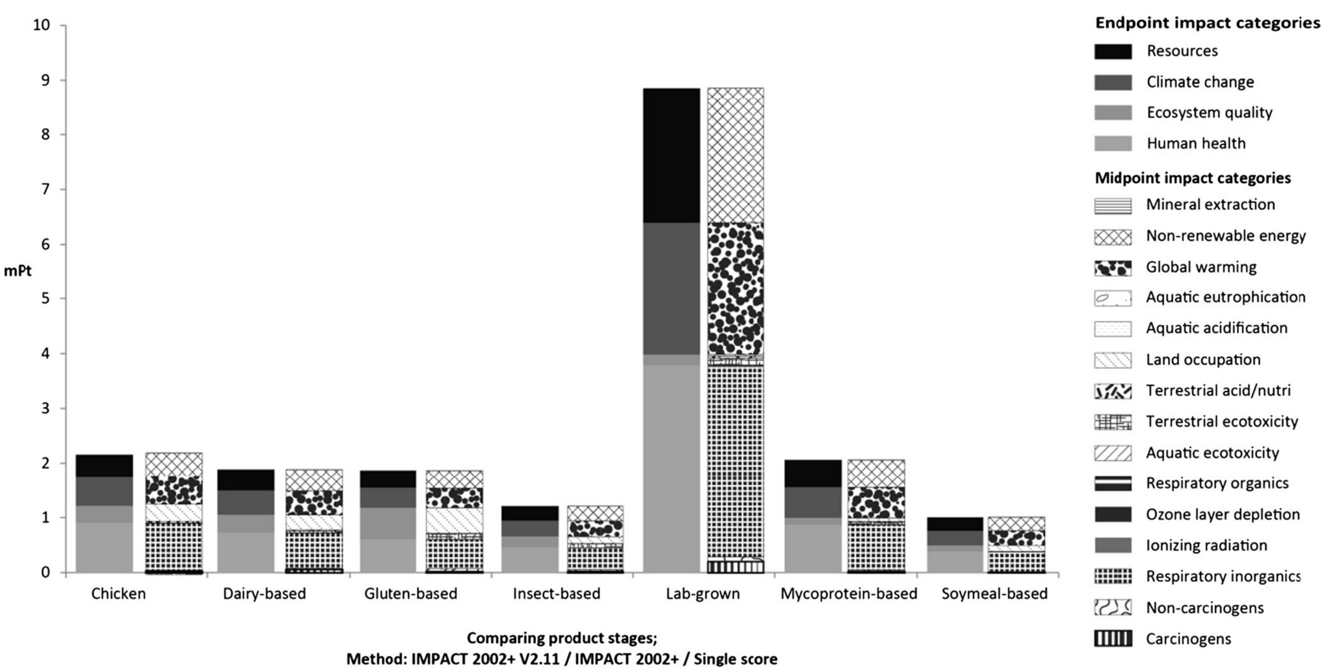


Fig. 8 Single-score product comparison FU 1 kg of ready to use product (from cradle to plate) with IMPACT 2002+ methodology

Table 2 The comparison of main characterization results of the study with literature data

Product	Climate change, kg CO_2eq./1 kg (FU)			Land use/occupation, m^2/1 kg (FU)			Non-renewable energy use, MJ/1 kg (FU)		
	This study	Literature data		This study	Literature data		This study	Literature data	
(1) Chicken	5.2–5.82	1.3–1.4	(Katajajuuri et al. 2008; Pelletier 2008; Cederberg et al. 2009)	3.85–3.89	2.1–5.0	(Alig et al. 2012)	51.64–63.4	1.3–14.9	(Williams et al. 2006a, b; Katajajuuri et al. 2008; Pelletier 2008)
		1.6–2.4	(Alig et al. 2012; Wiedemann et al. 2012)					12.8–20.4	At processing gate (Wiedemann et al. 2012)
		1.5–5.5	(Williams et al. 2006a, b)		2.2–7.3	(Williams et al. 2006a, b)		17.3–26.9	(Alig et al. 2012)
								54	(Ellingsen and Aanondsen 2006)
(2) Dairy based	4.38–4.95	3.79–6.2	(Blonk et al. 2008; Head et al. 2011)	3.32–3.41	2.94–3.1	(Blonk et al. 2008; Head et al. 2011)	48.79–59.1	55.5	(Blonk et al. 2008)
(3) Lab grown	23.9–24.64	1.8–2.3	(Tuomisto and de Mattos 2011; Tuomisto and Roy 2012)	0.39–0.77	0.18–0.23	(Tuomisto and de Mattos 2011; Tuomisto and Roy 2012)	290.7–373	25.2–31.8	(Tuomisto and de Mattos 2011)
		10	Proteins (Tuomisto and Roy 2012)					31,700	(Tuomisto and Roy 2012)
(4) Insect based	2.84–3.02	2.7	Fresh insects (Oonincx and de Boer 2012);	1.5–1.52	3.6	Fresh insects (Oonincx and de Boer 2012)	32.0–40.4	34	Fresh insects (Oonincx and de Boer 2012)
		20	Proteins (Van Huis et al. 2013)		18	Proteins (Van Huis et al. 2013)		170	Proteins (Van Huis et al. 2013)
(5) Gluten based	3.59–4.03	1.55	Gluten powder (Deng et al. 2013)	5.5–5.82	2.07	Gluten powder (Deng et al. 2013)	39.7–49.2	1.4–1.7	Wheat (Nemecek et al. 2001)
								2500	Edible wheat (Tuomisto and Roy 2012)
(6) Soy meal based	2.65–2.78	2.54–3.72	Tofu (Head et al. 2011)	1.06–1.44	1.95–2.49	Tofu (Head et al. 2011)	27.78–36.9	1.5–2.3	Soy (Pelletier et al. 2008)
		0.34–0.9	Soy meal (Dalgaard et al. 2008)		3.0–3.6	Soy meal (Dalgaard et al. 2008)		3000	Edible soy (Tuomisto and Roy 2012)
(7) Mycoprotein based	5.55–6.15	2.4–2.6	(Blonk et al. 2008; Head et al. 2011)	0.79–0.84	0.41–1.2	(Blonk et al. 2008; Head et al. 2011)	60.07-76.8	38.0	(Blonk et al. 2008)

gate (Nemecek et al. 2001; Pelletier 2008; Cederberg et al. 2009; Alig et al. 2012; Oonincx and de Boer 2012), dead weight at slaughterhouse (Williams et al. 2006a, b), product at processor gate (Ellingsen and Aanondsen 2006; Blonk et al. 2008; Dalgaard et al. 2008; Tuomisto and de Mattos 2011; Tuomisto and Roy 2012; Wiedemann et al. 2012; Deng et al. 2013), product at retail (Katajajuuri et al. 2008; Head et al. 2011), or further processed product at processing gate (Van Huis et al. 2013). Moreover, environmental performance data of meat substitutes were varying very considerably in literature, which made the comparison not reliable.

Land use change (LUC) impacts were not included in the main study, as most of the crops, used as raw materials of substitutes, are not characterized as those having LUC (Milà i Canals et al. 2013). The comparison was based on average world data, and therefore, in most cases, LUC were not observed for crops at a global level. At the same time, such crops as maize, soya, carrots, and palm oil, used for meat and substitute production, were responsible for LUC at global levels. LUC impacts would add additional GHG amounts to those presented in Table 2. Dairy and insect-based substitutes would add 0.27 kg CO_2eq. to climate change category due to LUC. This would not change their relative position in comparison. The chicken meat was responsible for additional 0.8 kg CO_2eq. per FU. In this case, it became the second less sustainable product among compared (FU 1 kg). However, it would not affect the performance of chicken meat with alternative FU. Soy meal substitute was responsible for additional 1.08 kg CO_2eq. due to LUC. Taking into account the overall GHG emissions by soy meal substitute (2.65–2.78 kg CO_2eq.), it was a significant change (more than a quarter). However, it would not affect the overall comparative performance of soy meal-based substitute, leaving it among the most sustainable.

In order to indicate the possible influence of selected method of assessment (ReCiPe), we also performed an analysis with other available methodologies (IMPACT 2002+; ILCD 2011 Midpoint; CML-IA baseline V3.00/EU25+3, 2000). The results indicated similar rates. They were in the ranges indicated in Table 2. The greatest impact is reflected in categories of climate change (global warming), fossil depletion (non-renewable energy consumption), and particulate inorganic formation (respiratory inorganics). For some products (chicken, dairy based and gluten based), land use category was responsible for 5–10 % of impact (FU 1 kg). Therefore, a decrease in energy consumption and non-renewable energy use could significantly decrease the environmental impact (climate change and fossil energy categories) of compared products.

The variations of results due to the different FU and methodologies indicated that soy meal-based meat substitute is a more sustainable alternative (at a current technology development level). Its performance, however, could be further improved if the production of the substitute would be performed close to the soy-growing agricultural regions. Chicken meat and insect-based meat substitute performed worse than soy meal substitute but better than the other alternatives.

The worst environmental performance was noted for lab-grown meat followed by mycoprotein meat substitute due to the higher consumption of energy. Lowering that consumption with further technology development would decrease their negative impact. It is especially evident to lab-grown meat technology, which functions today at a lab scale only (Tuomisto and de Mattos 2011). However, the technological development and adaptation is also possible for other meat substitutes as well (such as insect based). Taking into account the need for additional protein sources, which will be more sustainable than conventional meat, the ongoing LCA analysis of their development would be helpful to indicate the “hotspots” at the development stage of products.

We selected mass-based FU as a basis for the main comparison, which aimed to present the equivalent of mass portions at the consumer. However, the nutritional qualities of compared products were not equal. That is why the comparison of two alternative FU (based on food energy and protein digestibility) was included as a part of sensitivity analysis. Food energy is an integrated value of products, which is derived from food carbohydrates, fats, and proteins. It reflects a function of supplying an organism with energy to sustain its metabolism and movements. Therefore, the equal energy content of different products was a basis for one FU. The other FU reflected the main aspect of meat food consumption. The main function of meat consumption is recognized for its protein content (Jiménez-Colmenero et al. 2001). The content of proteins and their digestibility varies among meats and meat substitutes. Supplying a consumer with the same equivalent of digested proteins was the basis for second alternative FU selection. At the same time, we acknowledge that energy and protein contents are not reflecting a complete spectrum of meat nutritional values. It is not reflecting differentiations in the qualities of amino acid contents, amounts of vitamins, fat and fatty acids etc. Further assessments, which indicate nutritional value differentiations, based on integrated single nutritional FU would be a good approach to follow.

Selected meat and meat substitute products have different levels of technology development. Industrial chicken production is a highly efficient and has a long history of technology development. Meat substitutes, based on dairy products, mycoprotein, soy meal, and gluten, are presented at industrial production scales, but their production could be further improved and adjusted. They are on the market of meat substitutes’ production rather recently comparing to the chicken production. Although, the mentioned substitutes and chicken production are assigned to technology readiness level (TRL) 9 (European Commission 2014). The third group of lab-grown meat and insect-based meat substitute was considered at the lab scale (limitation owing to the availability of data). It is not produced industrially yet and assigned with TRL 4. However, the performance of lab-scale technologies could be improved dramatically in the nearest future while efficient production of chicken would not probably change. At the same time, the development and improvement of different technologies are not a straight forward process. It strongly depends on production structural components (type of technology, production complexity) and system components (research interests and market availability; Zschieschang et al. 2012). For example, insect-based meat substitutes would probably rely on existing developed technologies for texturized vegetable products and, therefore, could be introduced to the market faster than lab-grown meat. For the last product, the production is complicated by the need to develop technologies for all the stages of production. The predictability of data changes, as well as LCA results with scale up and improvement of technologies, is a complex problem, which was not set as an objective for this study, but would be a good approach for further research.

5 Conclusions and recommendations

The analysis included three functional units (FU). The first FU was mass-based and represented as 1 kg of a ready-to-eat meal based on chicken or analyzed meat substitutes. The results showed the highest impact for lab-grown meat (3), which had been foreseen owing to the early stage of technology development. The high impact was explained due to the high energy demand for the medium and meat-growing processes. Second highest impacting products were mycoprotein based (7) and chicken (1), which was associated with high energy demands (7) and agricultural feed-growing activities (1). The study showed the lowest impact for insect-based (4) and soy meal-based (6) substitutes, which explained with the use of effective processing and growing technologies and by-products use and side stream utilization. Dairy-based (2) and gluten-based (5) meals had a medium impact as they had higher demands (compared to chicken) for transportation and energy for the product processing.

The second FU was associated with leveling according to the food energy level (3.75 MJ energy content of fried ready-to-eat meal based on chicken or analyzed meat substitutes). The sensitivity analysis showed considerable changes of results in the environmental performance of products. As in the main FU study, lab-grown meat (3) had a leading impact and mycoprotein-based analogue (7) was the second one. The best performance was indicated for chicken (1), dairy-based (2), and gluten-based (5) substitutes. Soy meal-based (6) and insect-based analogues (4) had medium impacts.

The third FU reflected the function of supplying a consumer with the equal amount of digested proteins (0.3 kg dry matter). The results indicated the worst performance for lab-grown meat (3), followed by mycoprotein-based analogue (7), making these two substitutes the least sustainable choice at a given level of technology development. The best performers were soy meal (6) and insect (4) analogues and chicken (1). Gluten (5) and dairy-based (2) substitutes had medium impacts. In most cases, soy meal-based and insect-based substitutes perform at low or medium levels of environmental impact, which indicates their potential for being more sustainable meat alternatives. So, the FU in meat substitute comparison studies played an important role, which should be considered in the selection of comparison basis.

The comparison of the results with literature data was not indicative, taking into account high literature data variability (system boundaries, FU, allocation). Further studies of evolving meat substitutes' production technologies are needed. In the best "ideal case," it is needed to perform the comparison of different meat substitutes in the same production conditions with analysis based solely on field data. Performed analysis did not indicate all the alternative emerging meat substitutes (algae based, egg based, etc.) which might have a better environmental performance than indicated options.

The article also raised an important question of a functional unit for meat substitutes' comparison. Changes of the FU altered results quite dramatically, and therefore, the development of a FU which would reflect the complete integrative nutritional function of meat substitute is needed. It is obvious that meat substitutes have different nutritional profiles and, therefore, nutritional value. At the same time, different aspects of nutritional quality (protein and amino acid content, vitamins, fat and fatty acids, etc.) vary in different proportion in meat substitutes. Therefore, it is necessary to develop a complex nutritional value estimate, which would reflect the qualities of meat and meat substitutes for further studies.

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