

# Agri-Food Waste Streams Utilization for Development of More Sustainable Food Substitutes



Sergiy Smetana, Kemal Aganovic, Stefan Irmscher and Volker Heinz

**Abstract** Substitution of food out of alternative biomass sources is aimed to supply consumers with food products similar in nutrition and with lower environmental impact compared to conventional products. At current state of development, meat substitutes are not competitive with chicken meat, except for plant based meat analogs (although they have weaker nutritional profile). Upscaling, further technological development and use of agri-food waste as main source substrate can assure the environmental benefits of insects (2 kW h of energy, 1 kg CO<sub>2</sub> eq., 1.5 m<sup>2</sup> of land and 0.1 m<sup>3</sup> of water) and single cell products (10 kW h, 2–4 kg CO<sub>2</sub> eq., 0.5 m<sup>2</sup> of land and 0.25 m<sup>3</sup> of water), making them more competitive compared to industrial chicken production. The results of the current research are preliminary and further studies are required to assure the industrial applicability of agri-food wastes use for food production.

## 1 Introduction

Food production is one of the most important human industries, which can be responsible for a majority of environmental impacts in developed countries [1]. The main causes for such impacts relate to overpopulation, growing demand for consumption of animal derived products and high rates of food waste. While some research targets development of solutions for separate issues, more recent sources indicate the need for a more holistic and systematic change of the complete food production chain [2, 3]. The substitution of traditional foods with alternative analogs produced by non-traditional methods is foreseen as one example of sustainable transitions [4]. However, considering a complete life cycle of food substitutes, their performance is not always cost efficient and environmentally beneficial [5–7]. Therefore, a more sustainable status of food transitions should be confirmed with extensive research of economic efficiency, environmental advances and social acceptability.

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Substitution of environmentally high-impacting meat with more sustainable alternatives is becoming not only necessary, but also popular through vegetarian, vegan and flexitarian diets. Numerous food products are under recent development to cover the requirement of consumers in more environmentally sustainable and yet nutritionally beneficial food analogs. Several scientific studies indicated that meat substitutes had a lower environmental impact than meat [8–17]. Even though the environmental benefits of texturized plant protein substitutes (soybean, pea, lupine, etc.) are well-known and proven [18, 19], their nutritional and organoleptic qualities require improvement [20, 21]. Other analogs based on milk, mycoproteins, insects, microalgae, etc., are not environmentally beneficial in all of the cases [5, 6, 22, 23], but have improved nutritional profile, more similar to animal derived products [23–26]. Developments in cellular agriculture claim that creation of meat, milk, cheese and eggs without agricultural inputs is more environmentally friendly due to the avoidance of agricultural stage [7, 27]. Despite the complete nutritional identity between cellular products and animal derived foods, the environmental impacts of cultured food are usually higher due to low Technology Readiness Levels (TRL) and increased use of energy as well as biotechnological raw materials [5, 7, 28]. Although, few comparative studies of environmental performance and nutritional value of meat substitutes to animal derived products were published [5, 10, 15], the analyses did not cover complete variety of food analogs and production technologies. Even though further environmental optimization measures for food substitutes are known, they are rarely analyzed and reported in literature. Upscaling of production, reduction of energy consumption, reduction of waste amounts and utilization of waste streams as raw materials are among the most known measures, which should be analyzed to identify future potential of food substitutes. Therefore, it is necessary to perform a holistic systematization of more sustainable production potential for “food of the future” based on innovative and emerging technologies of alternative protein products supply. Such systematization should provide an answer on more sustainable ways to produce food substitutes with existing industrial infrastructure and the potential of improvement with the use of agri-food waste.

## 2 Methods and Materials

The study included two main stages. First, it relied on a systematic review of research literature addressing the production of food substitutes and their associated environmental impacts. It was compiled with own results on the LCA of food substitutes. Further, the authors assessed the technological potential of agri-food waste application for the design of food substitutes. This way, the first part of the study indicated the most promising options of food substitute’s production from environmental perspective, while the second part estimated further potential for environmental impact improvement. The second part resulted in generalized comparison model (matrix) used for the assessment of environmental impact of food production scenarios with application of waste streams as a main source of raw materials.

The study relied on the results of Life Cycle Assessment (LCA) according to ISO standards (ISO 14040-14044) [29, 30] present in literature (Part 1 of the study) and own assessments (Part 1 and 2).

The first part of the research included literature search on Google Scholar online platform with key words “environmental impact”, “LCA” and “Life Cycle Assessment”, “substitutes”, “food products” for the period of 10 years (2007–2017) and returned with 580 publications identified. Further search was refined with additional key words: “meat substitutes” (64 results), “meat analogs” (7 results), “cultured meat” (21 results), “milk substitutes” (12 results), “dairy substitutes” (10 results), “alternative protein sources” (21 result). The resulted literature (135 references) was analyzed in detail to identify the environmental impacts of food substitutes. It was identified that 41 study presented results on various aspects of food substitutes LCA. We relied on the data from the literature with adaptation to the requirements of current study (attributional LCA with four impact categories of global warming potential, non-renewable energy use, land use and water footprint based on IMPACT 2002+ and ReCiPe methodologies) [31, 32]. It was aimed to answer the research question on identification of more sustainable food substitutes presented in literature. Environmental impact of food substitutes was compared in between and with conventional products.

The second part of the research addressed the potential of environmental impact improvement with the use of agri-food waste streams. The estimation of the potential required the assessment of current uses of agri-food wastes for food biomass production and further technological potential assessment for food design. The second part in a great degree relied on own data of industrial processing trials (DIL, Quakenbrueck) and background data available in literature and relevant databases (Agri-footprint and ecoinvent 3) [33, 34] with modelling in SimaPro 8 software. The results on Technology Readiness Level (TRL) and potential of agri-food waste use (includes all the types of food waste generated along the supply chain) was included into matrix (Table 1), which allowed overview of conventional foods substitution with potentially more sustainable alternatives. Furthermore, the analysis of agri-food waste potential included the comparison of nutritional profile of resulting products with benchmark food.

## 3 Results and Discussion

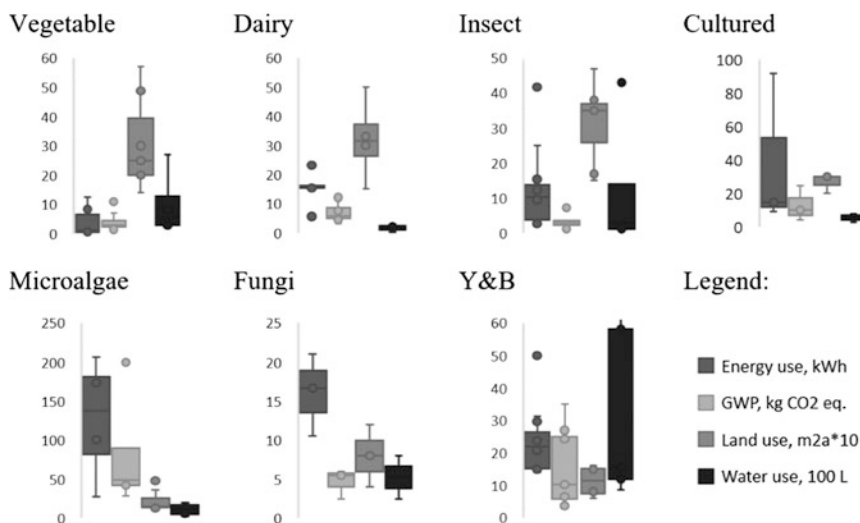
### 3.1 *Environmental Impact of Food Substitutes*

The analysis of environmental performance of meat substitutes included production and processing of protein sources based on plant proteins (soya, lupine, peas, gluten, etc.), dairy products, insect biomass, cultured meat, microalgae biomass, fungi, yeast and bacteria (Fig. 1). The analysis demonstrated that at despite certain comparability of the impacts for different sources of protein biomass, in many

**Table 1** Matrix of agri-food waste application potential for the production of food substitutes source biomass in relevance to technology readiness levels

Source of biomass for substitutes	Substituted animal derived products			
	Meat	Dairy	Eggs	Fat
Plant	IX/9	IX/6	VIII/6	IX/9
Milk	IX/0	n/a	VI/0	IX/0
Insect	VI–IX/7	I–VII/8	VI–VII/8	IX/9
Cultured	VI/4	VI/4	VI/4	VII/6
<i>Single cell protein</i>				
Microalgae	VII/5	VIII/5	VIII/5	IX/7
Fungi	IX/6	IX/5	VIII/5	IX/9
Y&B	VII/6	VI/6	VIII/6	VI/6

Note I–IX—Technology readiness level (TRL) after [48] for the application of source biomass to substitute animal derived products; 0–9—potential of agri-food waste application for the source biomass production (with 0—no potential identified to 9 confirmed industrial application possible); Y&B—yeast and bacteria



GWP - global warming potential, Y&B - yeast and bacteria, the assessment is based on [5,6,10,11,14,18,19,35–40] and own calculations for insects, microalgae and yeasts and bacteria (Y&B) according to the production data and inventories [39,41]

**Fig. 1** Environmental impact of meat substitutes based on various alternative sources of proteins

cases, there were a few limitations for a reliable distinction between the comparable products. On the one hand, there were wide ranges of environmental impacts (e.g. due to land use for plant based substitutes, energy use for cultured meat and microalgae, water use for yeast and bacteria), and on the other hand there was a lack

of available studies, data sources and relevant models in order to narrow down the ranges of environmental impacts (e.g. water use for dairy based, microalgae and cultured meat substitutes).

Despite mentioned limitations, it was possible to indicate that according to the current state of TRL the most promising sources of proteins in terms of energy consumption were plant and insect protein biomass (grown on commercial chicken feed). Meat substitutes based on biomass derived from dairy, yeast and bacteria had higher level of energy consumption, but also high potential for further development. Alternative sources of proteins had low impact on climate change (comparable with chicken 2–4 kg CO<sub>2</sub> eq. and pork 4–6 kg CO<sub>2</sub> eq. per kg of meat) for all of the sources, except for meat substitutes from microalgae (related to variety of production conditions). Land use impacts were comparable between alternative sources of proteins (2–4 m<sup>2</sup> a per kg of product, vs. 5–7 m<sup>2</sup> for chicken and 7–8 m<sup>2</sup> for pork). Fungi, yeast and bacteria based sources of proteins were exception and had lower land use impact (up to 2 m<sup>2</sup> a year<sup>-1</sup>). Water footprint was quite similar between different protein sources with lower impacts associated with microalgae and fungi biomass. Benefits of water consumption of dairy and insect based meat substitutes, as well as of cultured meat could not be demonstrated due to the lower data quality.

In terms of nutritional quality, the most identical substitute to meat was produced by cellular agriculture methods (cultured meat). However, due to muscle purity, meat substitute produced by cellular agriculture usually consists of lower fat content than traditional meat. Plant based meat substitutes are well researched and documented, with high presence on the market. At the same time, the diversity of vegetable protein sources and their unbalanced nutritional composition set difficulties for the complete substitution of animal derived products.

Insect and dairy based food substitutes are characterized with excellent nutritional qualities similar, or often more beneficial than traditional meat products. Milk based protein products usually have a moderate protein and fat content (10–14% and 8–10% respectively). However, dairy based protein concentrates and isolates can serve as a high protein additive for human consumption. Insects can be considered as a good source of proteins (up to 77% dry weight), fats (up to 62% dry weight) and polyunsaturated amino acids [42]. Moist cooked products, based on whole mealworm and depending on the processing technology, resulted in products with 22–30% proteins and 2–20% fat (own data). However, the limiting factor of insects' application for food and feed could be low amounts of methionine [43].

Single cell production (fungi, algae, yeast and bacteria) can provide excellent sources of proteins (30–65% in dry weight) and fats (up to 20% in microalgae), but they are also a source of nucleic acid (3–12%), which can be a serious obstacle for the direct use in food, as it might cause health complications [44].

### ***3.2 Potential of Agri-Food Wastes Application for Production of Food Substitutes Biomass***

Application of agri-food waste can be foreseen as one of the key solutions to improve the sustainability of current food production. The main options of dealing with agri-food waste include prevention, creation of food banks (or storages), valorization for animal feed and other purposes (e.g. recovery of nutrients or extraction of highly valuable components, recycling of proteins for the new products), reuse (application for other purposes like generation of energy and heat), composting and landfilling [45–47]. Current study dealt with a combined approach addressing prevention of food wasting and food waste valorization, when agri-food wastes are assessed from the position of feeding substrate or media for insect and single cell production, as well as for meat culturing and direct application as a source of plant protein biomass (Table 1).

TRL plays an important role for the identification of opportunities for the agri-food waste application. Low TRL do not allow for the effective modelling of food substitutes production based on agri-food waste. Nevertheless, it was identified that direct application of agri-food waste for the plant based food substitutes is very challenging, but possible. Most known examples of such application include the use of soybean meal and okara as components of composite foods for direct human consumption. Side streams of plants processing usually fall in this category and can be utilized as a source for food. Main challenges were associated with assurance of food safety and adequate biomass quality (as in case of waste from consumers). On the other hand, application of processing side-streams (e.g. soybean meal, gluten), is well realized to produce texturized vegetable protein foods (Fig. 1).

Cultured meat production could potentially rely on cultivation media generated by bacteria fed on agri-food side and waste streams, however, such potential is only highlighted as possible in literature [14, 27, 28, 49]. In this case, the environmental impact could be reduced and reach the lower levels of impact indicated in Fig. 1. Such results correspond well to the result of the study [14], where it was reported that cultivation of meat on the cultured media from cyanobacteria could be environmentally beneficial. It is a previous conclusion and confirmation to the applicability in industrial scale is required.

The application of agri-food waste streams for single cell and insect production is an upcoming development, taking into consideration current improvements in TRL, performed and planned trials (projects CORNET “ENTOMOFOOD”, ERA NET-LAC “EntoWaste”). The biggest challenge here is associated with proper selection of suitable agri-food waste, which would assure the high efficiency of production and therefore would have a beneficial nutritional composition. In many cases agri-food waste corresponding to the identified properties, is represented by side-stream of food processing, used for animal feeding. So, another challenge relates to the application of multiple agri-food wastes as animal feed. The need to replace such feed material could result in higher environmental impacts than benefits from alternative proteins productions. At the same time, multiple sources of

agri-food wastes are not utilized as feed. In most of the cases the producer of a reference product covers the costs of transportation to the farms and thus pays for the utilization. Such precondition in combination with good nutritional qualities makes such agri-food wastes (e.g. mill brans, distiller's dried grains with solubles, brewery grains, milled pre-consumer waste) an excellent source for single cell and insect production. Successful application of agri-food wastes could reduce the environmental impact of food substitutes production with existing technologies (Fig. 1). Thus, the impact of insect-based food (1 kg) could be decreased to 2 kW h of energy use, around 1 kg CO<sub>2</sub> eq. of GWP, 1.5 m<sup>2</sup> of land use and 0.1 m<sup>3</sup> of water use. Single cell production can supply 1 kg of high quality protein food which would require around 10 kW h, emit 2–4 kg CO<sub>2</sub> eq., occupy 0.5 m<sup>2</sup> of land and consume 0.25 m<sup>3</sup> of water. Such environmental impact results make insects and single cell products more sustainable alternatives to meat and other foods.

## 4 Conclusions

Traditional food substitution with alternative biomass sources is becoming a necessity to design a more sustainable transition to the new food system. The current analysis, which included comparison of alternative protein sources according to the technology readiness level, nutritional profile and environmental impact, indicated the potential for the substitution of traditional food. Alternative sources of biomass can be used as food substitutes if their environmental and economic benefits are assured. It could be done thought the application of agri-food wastes and further development of production technologies.

The results of the current study indicated that state-of-the-art production of meat analogs based on milk, mycoproteins, insects and microalgae biomass are not competitive in terms of environmental impact to the benchmark meat (chicken in this case). The application of waste and side streams from agri-food production (molasses, distilled grains, grain brans) could potentially decrease the impact of insect and single cell products for their use as meat substitutes. Improvement in technologies for biomass processing is vital for the optimization of analogs based on single cell products. Similarly, processing stages play high importance for cellular-based products. However, high impact was associated with the production of culture media for meat production and raw resources of yeast derived milk, cheese and eggs. Cellular meat production at current state of TRL has a higher environmental impact than traditional production meat. With scaling up approach, a competing potential with beef and pork was shown, but not with chicken. The application of agri-food waste streams is complicated due to the need of providing a sterile culture media, although is possible for the cultured media production. Application of selected agri-food wastes to produce alternative sources of protein (specifically insects and single cell products) could result in more sustainable source of proteins able to compete with industrial chicken production.

The results of this study are preliminary and are characterized with high assumption uncertainties. However, it is possible to conclude that the application of circular economy principles to the production of traditional foods via innovative processing methods involving agri-food waste streams could allow for improvement of their environmental performances.

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