NEXTGEN PROTEINS

Bioconversion of Underutilized Resources into Next Generation Proteins for Food and Feed

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2 Executive summary

Food systems are of vital importance as they sustain human life and play a fundamental role in contributing to socio-economic sectors globally. Human population is expected to reach 9.7 billion by 2050, according to the United Nations' (UN) report on World Population Prospects. Recent research suggests that agricultural production globally must rise by 70% to meet this demand. However, there are significant challenges present in meeting this demand. These include the substantial negative environmental and social impacts the current system produces, including natural resource and land depletion, GHG emissions, waste generation, and resource and pollution inequality.

In order to face these challenges, the EU has set a research and innovation policy which covers the entire food chain to develop resilient and sustainable food systems. One means of achieving this objective is to increase the circularity and resource efficiency of food systems, especially via the production of alternative proteins. This report aids the EU policy by showing the circularity and environmental benefit potential of alternative proteins (algae, single cell protein, black soldier fly, and crickets).

Alternative proteins are an important field of research because protein is an essential macronutrient that is found throughout the body. Protein is made from amino acids, nine of which – the so called essential amino acids – must come from food. As such, protein is therefore a key part of any diet. In the scientific opinion of the European Food Safety Authority (EFSA), the average requirement of protein for healthy adults should equal 0.66 g protein/kg body weight per day. This rate is applicable to both high quality protein and to protein in mixed diets. A person weighing 80 kg should therefore consume 53 g per day.

Alternative protein forms an important subset of protein, defined by protein-rich ingredients sources from plants, insects, fungi (mycoprotein), or by means of tissue culture as a substitution for conventional animal-based protein. Research has already hinted at some benefits compared to traditional proteins, including higher nutritional values and less environmental impacts. However, further research is needed to confirm these initial studies.

Another recently rapidly expanding field of interest in the study of more sustainable food systems is the application circular economy (CE) principles to food systems. Most of the current research focuses on the circular economy approaches to food waste, however, the circular economy is much broader. CE principles are concerned with the creation of self-sustaining and sustainable value chain systems, in which materials are used repeatedly. Several studies have highlighted the benefits of circular food production, as opposed to traditional production, to the environment by using less resources and producing less waste and emissions. In addition, several case studies have highlighted the benefits of alternative proteins, in terms of nutritional value and the environment. Furthermore, socio-technical transition theory highlights how niche innovations, such as CE integration in food systems and alternative proteins, have the potential to disrupt socio-technical regimes, thereby bringing positive change. Others highlight the challenges associated with CE integration into food systems, in particular concerning alternative protein production. This work addresses both the potential benefits and challenges, specifically in relation to alternative proteins and circularity. Still, further research into CE principles in food systems is needed as it is difficult to apply one circular economy approach within the industry as broader applications are rarely relevant to individual food systems.

In this work, we took a case study approach to analyze four niche innovations in alternative protein production. The results of this work show that alternative proteins have the potential to reduce the environmental impacts from traditional protein production when compared to proteins which have a high environmental impact such as beef, where it was found that across all case studies alternative proteins had a 79-99% lower carbon footprint per kg protein. However, their processes still need to develop and scale in order to improve beyond lower carbon protein sources such as fishmeal derived from anchovy, which may be more representative of what alternatives may need to replace. It was seen that implementing circular economy actions into these processes would serve to reduce the carbon footprint of the different case studies (2-72% reductions across case studies). However, the results of the circularity assessment, indicators, and LCA results showed that not all circularity options are made equal. Even in the early development stages, alternative proteins production processes have been shown to differ substantially. Therefore, finding one-size-fits-all approach to implementing circular economy principles to the broader food system is difficult and would be of little practical use. However, applying a combined LCA and circular economy approach provides the benefits of understanding the most critical inputs and potential circular approaches to them, while simultaneously identifying outputs to be of use to other agents or which can be used repeatedly within the production process.

While this study is valuable to bridge the research gap within the circular economy literature especially relating to food systems, this work has several limitations. Firstly, there is some degree of criticism associated with the application of the theory of multilevel socio-technical transitions. This criticism concerns delineation, possibilities of cross-fertilization between regimes, and specific characteristics of niches to be able to be a platform for further development of the new technology. Another limitation more relevant refers to the differences in data quality of the four niche innovations studies. The results of an LCA are reliant on the data quality of the inputs, and thus for example in the case of cricket rearing in which all processing data beyond the rearing of the crickets could not be attained because they are performed by third parties, the quality of the results is then reduced. Lacking data can make a process seem more beneficial than it may actually be.

The results presented in this study are valuable, as they highlight policy implications to support the transition towards a circular economy in food systems. Future policies to support CE practices and sustainable food production could be aided through R&D funding. In addition, the EU could support the creation of a system for companies to report inputs and outputs, thereby acting as a circular economy database. This policy would add tremendous value to support CE implementation as low quality data forms one of the greatest challenges to date. Moreover, such a system might help facilitate partnerships between companies, which otherwise might not have formed due to the lack of a platform to find suitable partners.

3 Introduction

Food systems are an essential part of human life and play a fundamental role in contributing to socioeconomic sectors globally. Food systems are a source of substantial negative environmental impacts, however, such as natural resource depletion through the consumption of large amounts of water, nutrients, and energy, and other externalities, including land degradation, greenhouse gas (GHG) emissions, and waste generation. The inputs needed for agriculture, particularly feed production required to protein-rich livestock and nutrient loss is problematic (Jurgilevich et al. 2015). Agriculture requires specific nutrients (Nitrogen, Phosphorus, and Potassium) which are non-substitutable and the potential scarcity of phosphorus from phosphate rock, which is non-renewable, has prompted EU to list that nutrient as a critical raw material (EU Commission, 2020).

Human population is expected to reach 9.7 billion by 2050, according to the United Nations' (UN) report on World Population Prospects (United Nations, 2019). Recent research suggests that agricultural production globally must rise by 70% to meet this demand (Aznar-Sánchez et al., 2020). Furthermore, ameliorating agricultural productivity and sustainable food production are indispensable to nourish the more than 690 million people who are suffering from hunger today and the further 2 billion people by 2050. Achieving zero hunger by 2030 is one of the 17 Sustainable Development Goals (SDGs) of the UN. However, the current situation indicates that significant challenges exist in meeting this goal (United Nations, n.d.). Because of the impact and significance of food systems, the EU has set a research and innovation policy, Food 2030, to "transform food systems and ensure everyone has enough, affordable, nutritious food to lead a healthy life." The policy covers the whole food chain and emphasizes the resilience and sustainability of food systems to produce benefits for human health, the climate, planet, and communities. One means of achieving this objective is to increase the circularity and resource efficiency of food systems. In particular, the production of alternative proteins are one of the 10 pathways identified to achieve sustainability in the food system (EU Commission, n.d.). This report will focus on these aspects of the circularity and environmental benefits of alternative proteins to aid the policy's objective.

The circular economy, largely popularized by the Ellen McArthur Foundation, has become a primary objective of EU Environmental policy, with the EU having published a Circular Economy Action Plan (European Commission, 2020). The circular economy follows the principles of industrial ecology, in which outputs from processes should be seen as valuable inputs as opposed to "waste" (Ayres, 1989). The circular economy then widely applies such thinking to both technological and biological flows, to reflect nature's ability to be regenerative and use all parts of the biological chain as "food" for the next, as shown in Figure 1. This system would act as alternative to the current make-take-dispose system (Ellen MacArthur Foundation, 2019).

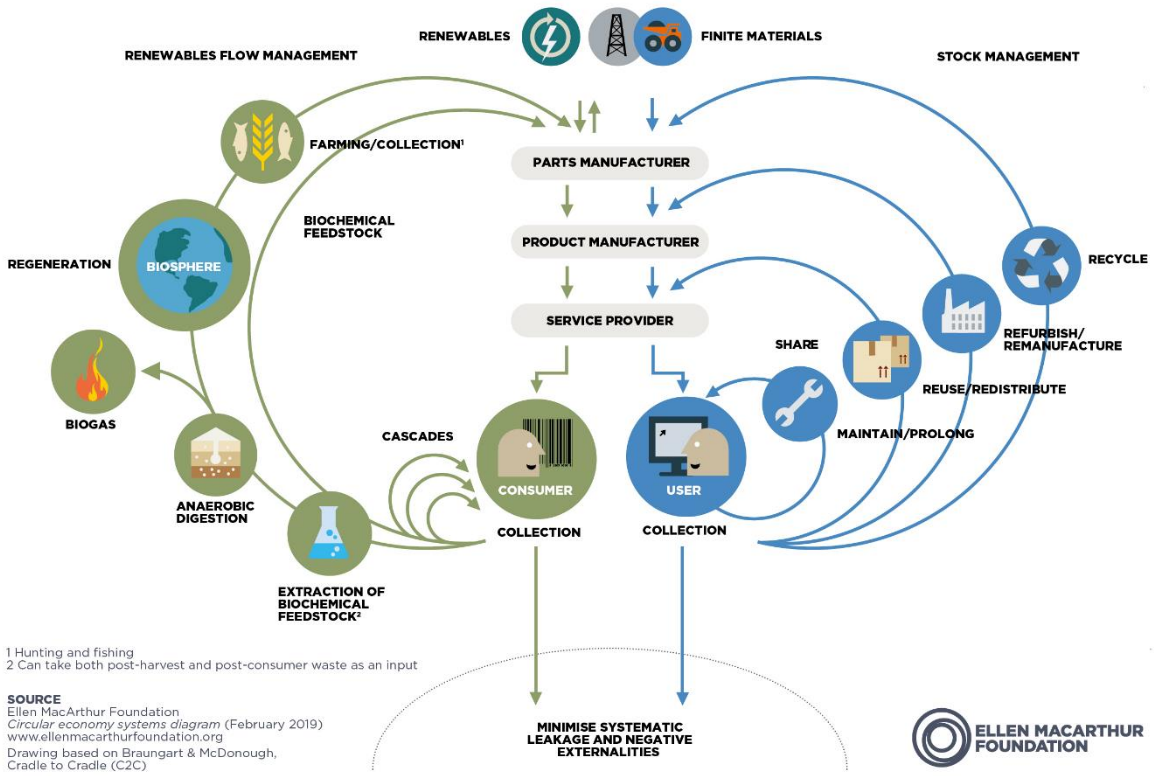


Figure 1. Illustration of the biological and technological circular economy (Source: Ellen McArthur Foundation, 2019)

The majority of research concerning the integration of circular economy principles into food systems focuses on reducing waste and lessening the usage of the environment as a sink for residuals. However, the circular economy is much broader as its principles are concerned with the creation of self-sustaining and sustainable value chain systems, in which materials are used repeatedly (Seuring and Müller, 2008; McDonough and Braungart, 2000). To highlight the advantages of the circular economy in food systems from an environmental point of view, Genovese et al. (2017) compare the performances of traditional and circular food production systems and show that the latter produce less carbon emissions, need fewer resources and recover more waste. Pagotto and Halog (2016) assess the environmental and economic performance of the entire food supply chain in Australia, highlighting the environmental externalities that the current linear production systems produce. Further, the authors present recommendations for the food industry based on CE principles and highlight the resulting potential for reductions in resource use.

On the other hand, Borrello et al. (2016) highlight a few key challenges to the implementation of circular economy into food systems despite its environmental benefits. For instance, regulations on animal by-products limit current feed lists for insects in the EU (Ojha et al., 2020). Other challenges concern reverse cycle logistics management (i.e. efficient collection systems), geographic dispersion of economic agents, technology development and diffusion, and acceptance of consumers to alternative foods (e.g. insects), among others.

Food production systems are complex and differ significantly between and within products. Therefore, research that focuses on the circular economy within the food system as a whole is quite general in nature. It is difficult to apply one CE approach within the industry as broader applications are rarely relevant to individual food systems. Hence, further research on specific food systems is needed to assess the potential for CE principles within the industry.

Alternative food systems challenge conventional agriculture, especially in terms of sustainability and circularity. Alternative protein forms an important subset, defined by protein-rich ingredients sources from plants, insects, fungi (mycoprotein), or by means of tissue culture as a substitution for conventional animal-based protein. Alternative proteins are beneficial in terms of nutritional value and their limited environmental impact. Alternative protein production is much more resource efficient and less carbon intensive. A recent report by Morach et al. (2021) found that a shift toward alternatives could reduce $CO2$ emissions by an amount equivalent to Japan's current yearly emissions, conserve water enough to supply a city as large as London for 40 years, and support biodiversity. Part of these advantages are due to the relatively low feed-to-food conversion loss rates of alternatives (Bashi et al., 2019). Research has demonstrated that insects produce significantly superior food conversion rates and utilize considerably fewer inputs, such as of land, fresh water, and feed compared to traditional livestock systems (Oonincx and De Boer, 2012). Another environmental benefit of insect production over livestock is the lower amount of GHG emissions during cultivation (Van Zanten et al., 2019). A literature review by Ojha et al. (2020) studies the application of life cycle assessments (LCAs) in evaluation of environmental advantages to insect rearing for food and feed production. Looking at 11 LCAs on different insects (mealworms, houseflies, black soldier flies, and crickets) the review concludes that while these initial studies point toward lesser environmental impacts of insect production, more research is needed to confirm these hypotheses. Another literature review focuses on the circular economy impact of insect frass in the development of sustainable agriculture by reviewing the results of 38 case studies. The review highlights that due to the high level of nutritional value of insects, the use of insect frass as a fertilizer could produce significant reduction of agrochemical use, promote plant growth, and increase tolerance to abiotic stress and resilience against pathogens and pests (Poveda, 2021). Furthermore, DiGiacomo and Leury (2019) demonstrate the potential of insect protein for inclusion in pig diets as a replacement to traditional feed sources and antibiotics. Cadinu et al. (2020) examine the feasibility of black soldier flies, houseflies, and mealworms to replace traditional feed for aquaculture and find that insects can, at least partially, replace common protein ingredients. Little research has focused on other alternative proteins, such as single cell proteins and algae. A review of nutritional studies by Becker (2007) highlights that algae proteins are of high quality and comparable to traditional plant protein sources. Suman et al. (2015) highlight the benefit to reduce land use and utilize waste in SCP production, while also stressing their nutritional value. However, further research is needed to evaluate the advantages that SCPs and algae protein pose, especially in terms of environmental benefits.

In addition to the environmental benefits of alternative proteins, they play an important role in terms of socio-technical transitions. Socio-technical transition theory considers the circumstances under which sustainable transitions occur and change socio-technical regimes. The Multi-Level Perspective provides an illustrative example of such a framework, as shown below in Figure 2. The picture illustrates the innovation that needs to occur and its integration within the existing socio-technical regime, and, if such a transition is successful, how it can change the socio-technical landscape. At the lowest level, the small arrows represent experimental niche innovations, some of which do not succeed, but others find fertile conditions and begin influencing society as they increasingly get involved in people's lives and the socio-technical regime (Jurgilevich et al. 2015). Such niche experiments provide a protective opportunity for user testing, business model development, and cultural and policy change needed to up-scale (Bulkeley et al. 2013). This is particularly relevant for newly evolving fields, such as alternative proteins, particularly one seeking to change a long-standing and culturally important regime such as traditional agriculture; arguably one of humanity's most long-standing regimes (Tso et al. 2022). It is these types of micro-innovations that, when successfully up-scaled, can begin to make significant changes to socio-technical regimes aiding to revolutionize the entire system to a more sustainable state. As the EU focuses on becoming more circular, small-scale innovations as those analyzed in this report are, therefore, of vital importance to the transition towards a circular economy.

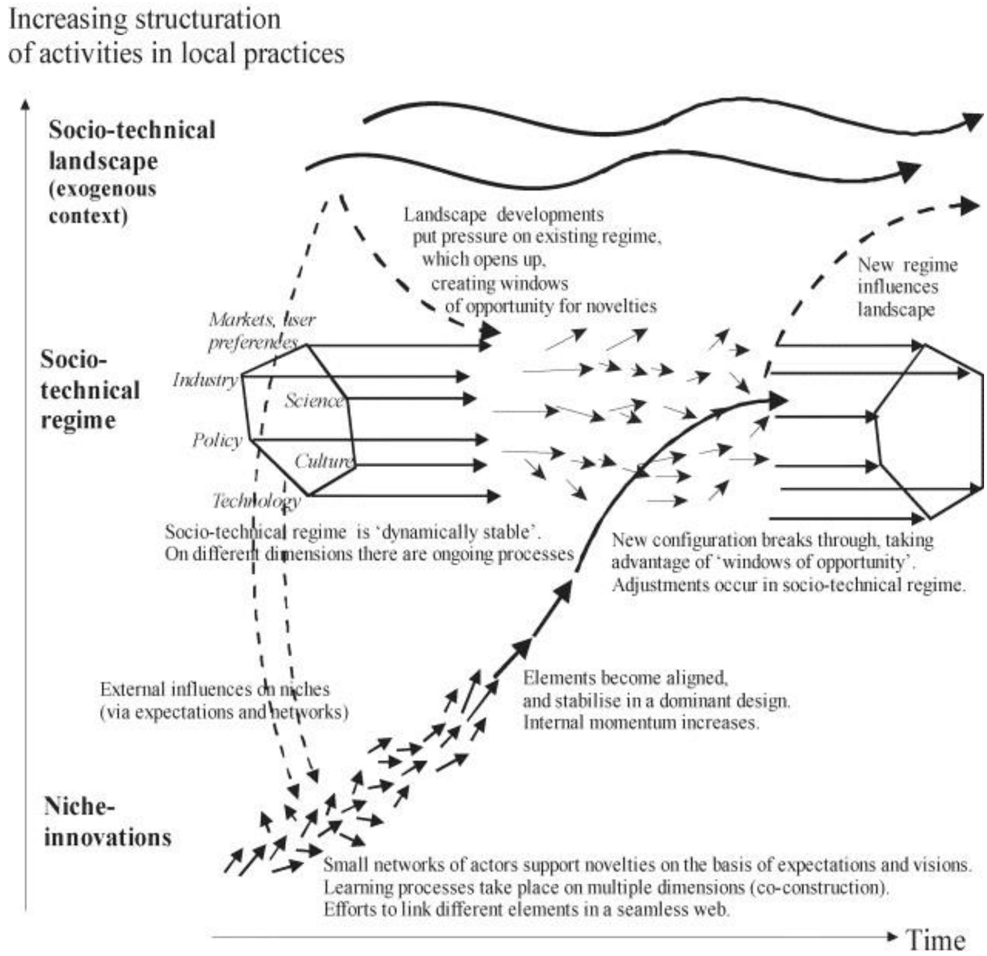


Figure 2. Illustration of the Multi-Level Perspective (Geels and Schot 2007)

In this work, we took a bottom-up case study approach to analyze four of such niche innovations. However, it is not sufficient to provide a single case study because as stated above, the production processes can be quite different for different alternative proteins. Rather, considered are four case studies of niche innovations of alternative protein production. Their circular economy potential will be assessed according to each case study's inputs and outputs using circularity indicators to get an early understanding of the environmental performance of these for niche innovations. Scenarios will then be developed for each case study regarding their circular potential, and these will be assessed using a life cycle assessment approach. Carbon footprint, water footprint, land-use, and energy-use will be considered. The results of these works will be compared to traditional protein production to understand the potential benefits of alternative protein production under different conditions.

This work serves to close the research gap identified by Esposito et al. (2020) in their review of the circular economy in the agri-food sector, where they identified a lack of tied circular economy and life cycle approaches. This work thus took this approach to answer key research questions regarding four niche innovations in the alternative protein sector.
These research questions are as follows:

1. What are the circular economy options of the four alternative proteins producers?
2. What is the potential to mitigate environmental impact of these options and how do they compare to traditional protein sources?
3. What are the main barriers to realize the potential?

To answer these questions, this work first assessed the CE potential of each case study according to different potential actions which could be taken for each input/output of each case study. Then, for each case study, a base case and circular scenario according to the most likely circular options that could be taken was developed. A life cycle assessment (LCA) was then performed for each of these scenarios. This approach allowed for a study into the environmental performance of novel food system innovations. Additionally, by assessing the circular potential, the goal of this work is to understand how the production systems for these alternative proteins could potentially be improved to be even more environmentally friendly. Ensuring that alternative proteins are more environmentally sustainable than the traditional food system models they are replacing is in support of the EU's goals towards a circular economy, and at scale, could serve in helping to ensure humanity stays within the planetary boundaries (Rockström et al. 2009; Steffen et al. 2015).

This report is organized as follows. First, an overview of each case study is provided to develop an understanding of the means of production. Next, the methodology of how the circularity potential is evaluated and LCA of each case study is described. The results of this work will then be provided. A discussion surrounding the benefits, challenges, and role of alternative proteins in the future food socio-technical landscape follows. The final section concludes.

4 Methodology

In this section we describe and give some detail to the four case studies being analyzed in this work. The four alternative protein case studies are protein production from algae, single-cell protein (SCP) production from yeast, black soldier fly cultivation and protein production, and cricket rearing and protein production. Due to confidentiality reasons, the case studies are described generally, with all case studies located within the EU. Here we also describe the analysis that is done in order to determine the circular potential for the four alternative proteins case studies.

Overview of case studies

Algae production: The algae production case study investigates the production microalgae and microalgae proteins through a continuous process (see Figure 3). First, a very small amount of algae biomass is introduced into the system and allowed to continuously reproduce. Water and CO2 are provided to the algae, as well as LED lighting to allow photosynthesis to occur. The light generates heat, which is then countered by cooling water being pumped through the system. Once the algae have been produced, protein is then extracted with the primary product being fish feed. The final product will take the form of dry powder at 71% protein by mass. The case study is located in a region with virtually 100% use of low-carbon electricity and heating.

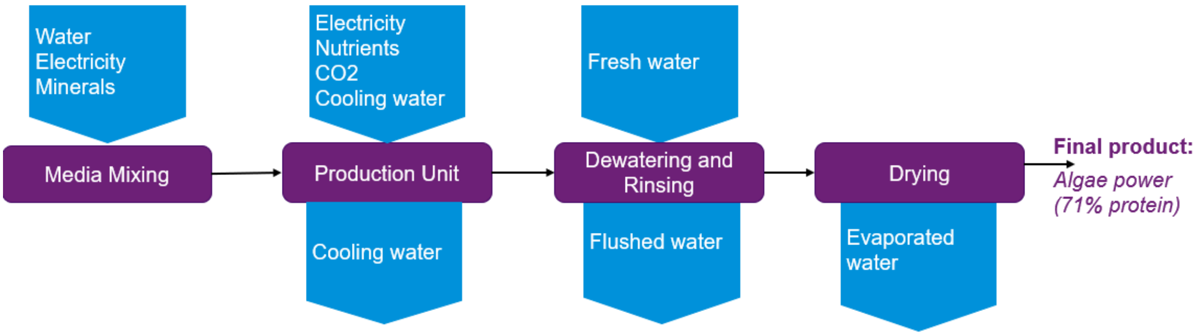
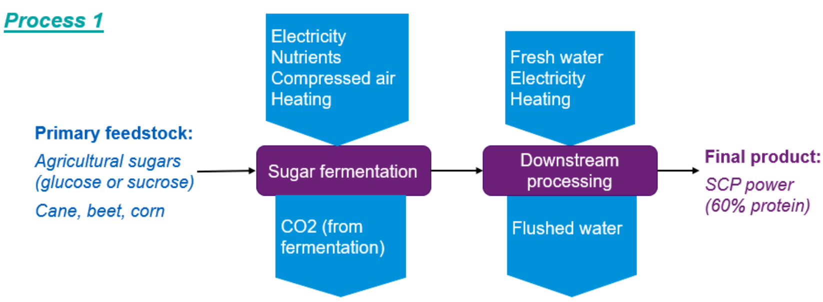


Figure 3. Algae case study simplified production process with key inputs and outputs

Single-cell protein (SCP): The SCP case study produces single-cell proteins, which are composed of dried inactived yeast. These microorganisms are grown through a fermentation process (seen in Figure 4), where the sugar source stems from sustainably managed agriculture or from hydrolysates of undervalorized agricultural by-products and wood residues. The output of this fermentation is then processed and dried into the final product, which takes the form of a protein rich powder (55% protein by mass) with potentially beneficial nutritional and organoleptic properties for industrial applications. The company sells its product as a protein ingredient both for human and animal consumption. Figure 4 features two diagrams because where the first process uses primary sugar products as the primary feedstock and the second process allows for the more circular use of agricultural by-products and wood residues. This process requires an additional process step however, and this is why the two processes are shown here. The case study's production location is in a European context with a low-carbon electricity grid but with fossil fuel produced heating.



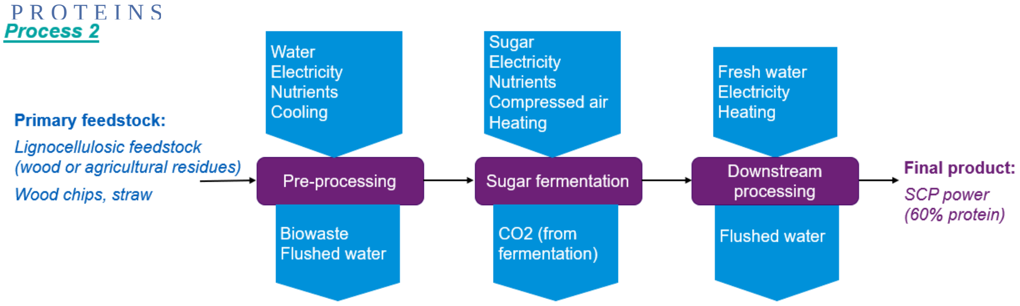


Figure 4. SCP case study simplified production process with key inputs and outputs. Process 1 illustrates the more linear production model, while process two illustrates the more circular production process which requires an additional processing step.

Black Soldier Fly (BSF): The case study produces protein from the black soldier fly. In the first stage, a powdered, liquid, and solid biomass is received and prepared into a substrate, which is then handled and placed in trays (see Figure 5). As the larvae begin to grow, the oviposition and fattening process starts, and this is then continued until the insects can be processed to protein concentrate. The final product consists of an insect meal form, which is a grinded powder with a 60% protein content. The case study's production location is in a European context with a low-carbon electricity grid but with fossil fuel produced heating.

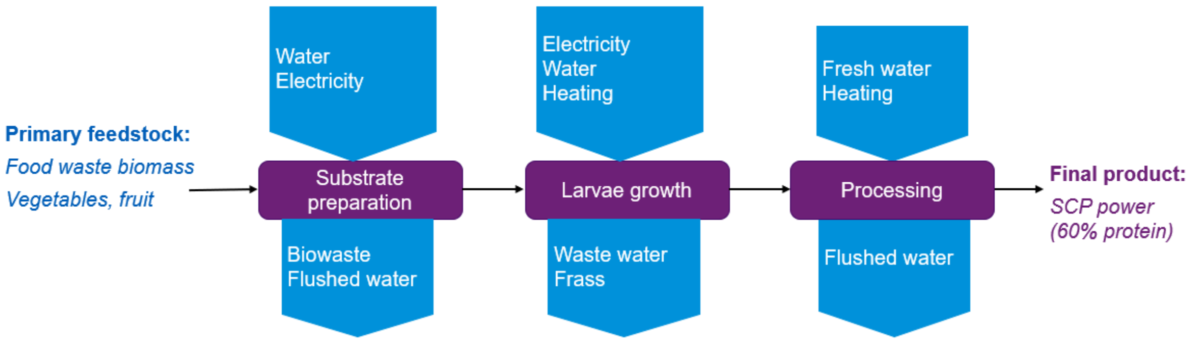


Figure 5. BSF simplified production process diagram

Cricket rearing: This case study produces its protein from crickets. The insects are reared, with the process beginning with the crickets being propagated by placing adult crickets with the egg-laying substrate, where the cricket eggs are then incubated and hatched (see Figure 6). The crickets are then grown out over approximately 30 days, after which the insects are inactivated through either a boiling or freezing process. The crickets are then processed into dry cricket protein. The company's production typically takes the form of dehydrated powder for food ingredient and direct consumption. From a consumer perspective, protein in conventional meat products may be regarded as the main competitor, but from the perspective of the protein user, soybean, and pea (legumes) protein can compete with protein from crickets. Due to lack of reliable data, the modelling of this case study's circularity potential more qualitative than quantitative, thus a circular scenario was not developed for this case study.

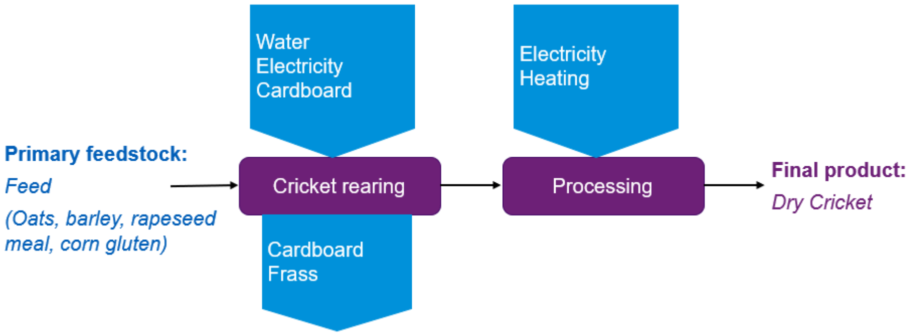


Figure 6. Cricket production simplified production process with key inputs and outputs

4.1 Environmental and circular assessment

The analysis was based on previous work with the described alternative protein producers which included an input/output process flow analysis, which is available in deliverable D6.1. For all inputs, e.g. raw materials and energy use, circular options were defined along with the most likely inputs. Similarly, outputs were considered, with the most likely use of the output and the circular option. The base scenario for all case studies was defined according to the current operating conditions of each case study. The circular scenario for each case study was then developed according to the circular options with the highest likelihood of application as well as for key inputs. For the circular inputs, activities could include, for instance, renewable energy, recycled water, while activities for circular outputs could be biowaste to anaerobic digestion and waste stream use in an industrial symbiosis with nearby industry. The circular options were then assessed based on their potential, i.e. the grade L for low potential, M for medium potential and L for large potential. The potential is a qualitative judgement base on the relative ability to implement each circular action option according to the potential barriers and the developed understanding of each process.

The circular indicators used to quantify the circularity potential were circular resources, circular energy, and circular water. These indicators only considered the inputs into the system, as most of the environmental benefits of circularity are largely seen during the input process, where the LCA impacts, except for avoided waste, will not be seen in the output process. Thus, these indicators are defined as the percent of total mass of resources and water, and total energy[1], which comes from circular sources. Life Cycle Assessments are then used to define the overall impact of the base scenarios and circular scenarios to show how much of an influence the circular options can have on environmental impact. The impacts analyzed were carbon footprint, energy footprint and water footprint measured using $kgCO_2$ equivalents, m^2 of natural land area consumed, and m^3 of water consumed per kg protein (the functional unit of the assessment. A comparison of the impact from competing protein product is also given for insight. The life cycle impact assessment methodologies used were ReCiPe Midpoint (H) method. The method was chosen because of its impact categories which measure water, land, and carbon impacts. Carbon impacts were measured in Global Warming Potential over a 100-year span (GWP100), water footprint from the Water Depletion (WDP)

[1] For energy, if using grid electricity, the renewables within the grid, if certificates were not purchased, were not considered as a circular activity, though in the LCA the grid factors considered the carbon intensity of the grid context in which the case study operates.

impact category, and the land footprint using the natural land transformation (NLTP) category. Ecoinvent 3.5 was the background database used for the assessment.

5 Results

In this section, the results of the work following the methods just described are elucidated. The first results will be a description of the circularity potential per case study with the probable circular scenario for each case study described, relevant to the operational context of the case study. The two scenarios for each case study were then described with the three circularity indicators. Using these scenarios, a life cycle assessment was performed for both the base and circular case for each case study in order to assess a) the current environmental performance of the alternative protein producers and b) the improvement in such performance that could be achieved using probable circular actions relevant to the production process of each of the alternative proteins.

5.1 Circular pontential assessment per case study

5.1.1 Algae

All the relevant inputs and outputs for the algae case study are shown below in Table 1. The primary resource inputs in Algae production are the nutrients needed for the algae to grow, fresh water which acts as the media in which the algae grows as well as cooling water to reduce heat generated by the lights, and manufactured CO_2. The algae production processes has a significant use of electricity due to the need for the light for the algae to photosynthesize. There is additionally a small amount of heat use related to the drying of the algae. When considering the circular potential for algae production, in terms of resources, it was determined that due to the relatively small existing market for traceable circular nutrients that the circular potential for these inputs were low. However, the potential to send CO_2 to be directly used as an input for algae production has been discussed, thus this was considered to have medium circularity potential. The use of low-carbon heat and energy were considered high due to the operating context of the current production facility.

Table 1. Algae circular assessment

Input/ Output	Source	Unit	Type of resource	Circular options	Scale of option	Barriers	Circular potential (H/M/L)
Input	Fresh water	kg	Water	Water recirculation	Internal to system	- Supply of freshwater -Need for uncontaminated water	L
	Minerals and nutrients	kg	Resource	Circular mineral inputs	Global	- Relatively small existing market - Green price premium	L
	CO2	kg	Resource	Direct supply from local industrial source or direct air capture.	Local	- Need for pure CO2 - Infrastructure required	M
				Supply of captured CO2 from global markets	Global/ regional	- Relatively small existing market - Green price premium	L
	Cooling water	kg	Energy	Wastewater from industrial source	Local	- Distance to partner - Infrastructure required	H
	Electricity	kWh	Energy	Use of renewable electricity	Local/ regional	- Supply of renewable electricity	H
				Purchase renewable energy credits	National/ International	- Must be in region where CO scheme exists - Green price premium	H

Input/ Output	Source	Unit	Type of resource	Circular options	Scale of option	Barriers	Circular potential (H/M/L)
	Heat usage	kWh	Energy	Use renewable heating	Local	- Must be located near a source of renewable heating - Lack of a CO market for renewable heat - Low agency to make change	L
Output	Media water	kg	Bio-waste	Industrial symbiosis with nearby industry	Local	- Need to find a suitable partner	L
				Anaerobic digestion	Local	- Need to find a suitable partner	L
	Flushed water	kg	Water	Industrial symbiosis with nearby industry	Local	- Need to find a suitable partner	L

Therefore, following the circularity potential described in Table 1, the circularity indicators can be seen in Figure 7. Since CO_2 was the only resource input with a high enough circularity potential and its representation as only 3% of the input mass, the circular resources indicator did not change significantly. In terms of energy, all heat and energy were considered circular to start because of the operating context. the circular potential was already maximized. Lastly, for the circular water indicator, the cooling water was already considered to be circular due to an industrial partnership already established, and this represents 99.5% of the water mass used in the production process, this was considered to already be nearly maximized in terms of circularity with the exception of the media water, which was not considered to have a large circular potential due to the need for uncontaminated water for the algae to grow.

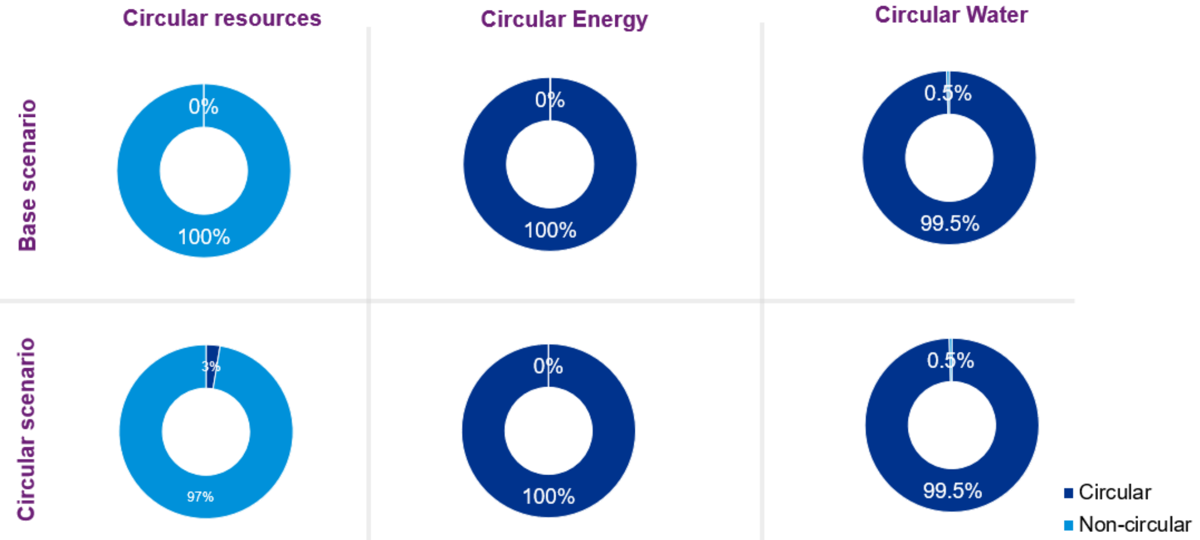


Figure 7. Circularity indicators for Algae production

5.1.2 Single Cell Protein

All the relevant inputs and outputs for the SCP case study are shown below in Table 2. The primary resource inputs in the SCP production were biomass, nutrients, electricity, heating, and water. For biomass which represents the primary input, the case study has already begun developing a circular model, represented in Process 2 of Figure 4, thus this input is considered to have a high circular potential. Similar to the algae production processes, the availability of options for circular nutrients on the markets was estimated to be low. Thus, it can be seen in the Figure 8 that the circular resources changed significantly due to the change in the primary biomass input. In terms of energy production, it was considered that while attaining renewable energy through the purchase of Guarantees of Origin (GOs) in the EU market (or a similar power purchase agreement ensuring the use of renewable energy) was an attainable circular option, such a market for heat does not exist. Therefore, in Figure 4 it can be seen that a large portion of total energy use (84%) could be considered circular. Lastly, for water, the circular potential to recirculate water internally to the system was considered high, and due to this, it can be seen that the water circularity indicator additional rose in the proposed circularity scenario.

Table 2. SCP circular assessment

I/O	Source	Unit	Type of resource	Circular options	Scale of option	Barriers	Circular potential (H/M/L)
Input	Bio-mass	kg	Resource	Use of circular input (i.e. wood chips, saw dust, or residual straw)	Local/ regional	- Circular biomass supplier at scale - Need for a consistent composition	H
	Nutrients	kg	Resource	Circular inputs	Global	- Relatively small existing market - Green price premium	L
	Enzymes	kg	Resource	Circular inputs	Global	- Relatively small existing market - Green price premium	L
	Water	kg	Water	Water recirculation	Internal to system	- Supply of freshwater - Need for uncontaminated water	L
	Cooling Water	kg	Water	Industrial symbiosis	Internal to system	- Need to find suitable partner	H
	Electricity	kWh	Energy	Use of renewable electricity	Local/ regional	- Supply of low-carbon electricity	M
				Purchase renewable energy credits	National/ International	- Must be located in region where CO scheme exists - Green price premium	H
	Heating	kWh	Energy	Use renewable heating	Local	- Must be located near a source of low-carbon heating - Lack of a CO market for renewable heat - Low agency to make change	L
Output	Solid losses (organic)	kg	Bio-waste	Industrial symbiosis with nearby industry	Local	- Need to find a suitable partner	L
				Anaerobic digestion	Local	- Need to find a suitable partner	M
	CO2	kg	Resource	Carbon capture of released CO2	Internal to system	- Small scale of carbon capture makes such a system uneconomic	L
	Water	kg	Water	Industrial symbiosis with nearby industry (such as agricultural use)	Local	- Need to find a suitable partner	L

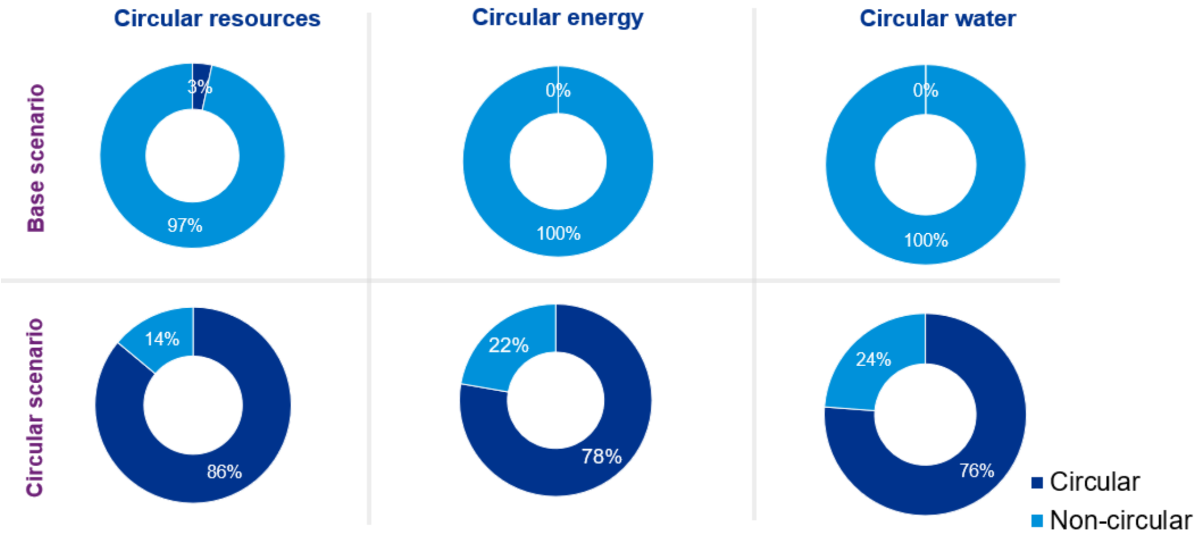


Figure 8. Circularity of resources, energy, and water inputs for SCP

5.1.3 Black Soldier Fly

All the relevant inputs and outputs for the BSF case study are shown below in Table 3. The primary resource inputs in the BSF production are biomass (mostly fruits and vegetables), nutrients, electricity, heating, and water. For the fruit and vegetable biomass which represents the primary input, the company has additionally already explored the circular potential of using food waste as opposed to purchasing fruits and vegetables directly, the circular potential for these inputs was thus considered high (representing 75% of the total resource inputs as shown in Figure 9). In terms of energy, similarly to the SCP case study, electricity was considered to be high due to the availability of GOs while circular heating potential was considered low due to lack of agency in making such changes. However, because the BSF case study uses more heat in their process proportionally than electricity, the energy circularity indicator did not see a large change (10%). Additionally, since the water needed for the BSF production was considered to be needed to be uncontaminated, it was considered that all water recirculation was considered low, and thus did not change in the circularity scenario.

Table 3. Black Soldier Fry circular assessment

I/O	Source	Unit	Type of resource	Circular options	Scale of option	Barriers	Circular potential (H/M/L)
Input	Wheat	kg	Resource	Organic wheat	Global	- Potential price volatility due to external shocks	M
	Fruits	kg	Resource	Food waste	Local	- Need for an efficient and incentivized local food waste collection system	H
	Vegetables	kg	Resource	Food waste	Local	- Need for an efficient and incentivized local food waste collection system	H
	Frass	kg	Resource	Internal circulation	Internal to process	- Requires system design	H
	Water	m^3	Water	Internal circulation	Internal to process	- Requires system design	M

I/O	Source	Unit	Type of resource	Circular options	Scale of option	Barriers	Circular potential (H/M/L)
	Electricity	kWh	Energy	Use of renewable electricity	Local/ regional	- Supply of renewable electricity	M
				Purchase renewable energy credits	National/ International	- Must be located in region where CO scheme exists - Green price premium	H
	Gas	kWh	Energy	Use renewable heating	Local/Municipal	- Must be located near a source of renewable heating - Lack of a CO market for renewable heat - Low agency to make change	L/M
Output	bio waste (liquid)	kg	Bio-resource	Internal circulation	Internal to process	- Waste may not be suitable for recirculation	M
				Industrial symbiosis with nearby industry	Local	- Need to find a suitable partner	L
				Anaerobic digestion	Local	- Need to find a suitable partner	M
	Waste Water	kg	Water	Industrial symbiosis with nearby industry (such as agricultural use)	Local	- Need to find a suitable partner	L
	Frass	kg	Bio-resource	Internal circulation	Internal to process	- Requires system design	H
			Bio-resource	Industrial symbiosis with nearby industry (such as agricultural use)	Local/Regional	- Need to find a suitable partner	M

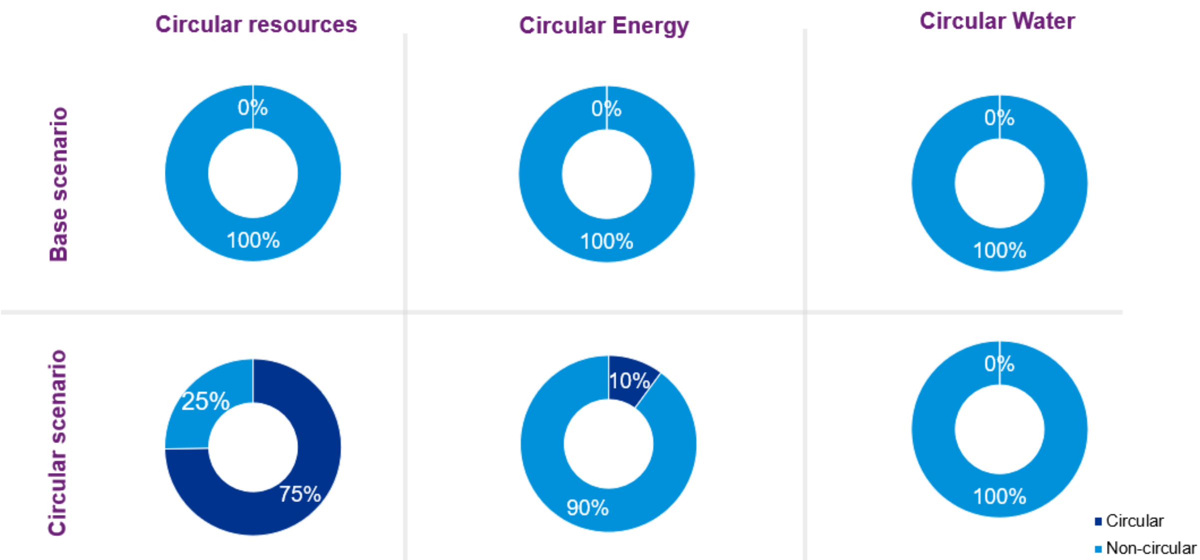


Figure 9. Circularity of resources, energy, and water inputs for Black Soldier Fly production

5.1.4 Cricket rearing

Lastly, the relevant inputs and outputs for the cricket rearing case study are shown in Table 4. Due to lack of data regarding processing of the crickets and the case study business model, a full circularity assessment was not performed for this case study. Rather, the circularity potential will be qualitatively described here. In terms of the feed provided to the crickets, tests should be performed to see if crickets would grow well using circular alternatives such as food waste, or that the feed can be produced in a more regenerative manner. Then, similarly to the other case studies, the nutrients were considered to have a low circularity potential to the lack of an existing market to purchase nutrients as such. Next, cardboard is used consistently in the process, and the potential to re-use waste cardboard or purchase should be seriously considered. Since only electricity is needed during the cricket rearing process, the ability to have circular electricity is high. However, though data was lacking regarding the culling stage, it is likely that heating is required during this stage, and due to this being done by third parties, it is likely that agency to ensure circularity in the use of this heating may be low. Lastly, as the water needed in the process is used as drinking water for the crickets, it is unlikely that this can be re-circulated in the system.

I/O	Source	Unit	Type of resource	Circular options	Scale of option	Barriers	Circular potential (H/M/L)
Input	Feed	kg	Resource	- Use circular feed - Ensure regenerative farming	Global	- Relatively small existing market - Green price premium	M
	Nutrients	kg	Resource	Circular inputs	Global	- Relatively small existing market - Green price premium	L
	Corrugated cardboard	kg	Resource	Make use of cardboard sent for recycling	Local	- need for an efficient and incentivized cardboard collection system	M
				Purchase with high recycling content	Global	- Green price premium	H
	Water	L	Water	Use of water from another industrial system	Local	- Need for clean water	L
	Electricity	kWh	Energy	Use of renewable electricity	Local/ regional	- Supply of renewable electricity	M
				Purchase renewable energy credits	National/ International	- Must be located in region where CO scheme exists - Green price premium	H
Output	Frass	kg	Resource	Internal circulation	Internal to process	- Requires system design	H
				Industrial symbiosis with nearby industry (such as agricultural use)	Local/Regional	- Need to find a suitable partner	M

5.2 Life cycle assessment

Using the circularity assessments and circular scenarios defined, a life cycle assessment for each scenario per case study was performed with the results for the three impact categories considered shown in Table 5. A comparison for 1 kg protein for human consumption protein (beef) and animal feed (fishmeal from anchovies) were provided as a benchmark. An analysis of the most significant inputs which led to greater than 80% of the total GHG emissions were provided to understand the drivers behind the results of each LCA result.

It can be seen that with the exception of cricket production, which was lacking significant processing data due to data availability, that the carbon footprint of the alternative protein case studies fell somewhere in between beef and fishmeal production. This is likely due to the fact that each case study is currently in the form of pilot projects and do not have the same economies of scale as traditional protein production facilities. However, each alternative protein saw a significant reduction in carbon footprint as compared to beef (79-99% reduction across all scenarios).

Further, Table 5 shows that the circular scenarios had different impacts across each case study. In the algae scenario, the circularity change was very insignificant because the operation was already largely optimized in terms of using renewable heat/electricity and industrial water supply as inputs. Thus, this did not change the carbon footprint of the product much (2% reduction). However, if this process were done using non-renewable electricity, the potential for the emissions to significantly increase exists due to the high electricity requirements per kg algal protein. Additionally, if cooling water was not sourced from an industrial source the water footprint would additionally be much more significant. For the SCP production case study, increased circularity significantly reduced the carbon footprint per kg SCP (72%). These benefits were largely seen due to the change in primary biomass source, from corn glucose to agricultural by-products, where even with the extra process significant benefits were seen. For BSF production, the circular potential had less of an effect because the most significant input even in the base case was the heat input, and without a suitable circular alternative considered in the circularity assessment, the carbon footprint could only be reduced so much (11%). If this input could be addressed and the wheat bran found a similarly lower carbon circular input, it is likely that the BSF could significant further reduce its carbon footprint. It is worth note that all case studies showed a reduction both in land use and water footprint, both of which are other material impacts of modern traditional agriculture. The only exception in terms of water footprint was in the BSF base case, where if fruits and vegetables were directly used, the embedded water footprint of traditional agriculture would then raise the water footprint. This example highlights the clear advantage of introducing a more circular model where food waste can be sustainably managed using BSF production.

Table 5. Scenario overview for diverse protein sources

Protein Source	Scenario	Carbon Footprint (CF) (kgCO2eq.)	Water Footprint (m3)	Land use (m2a)	Carbon Footprint Pareto drivers
Algae	*Base*	23.5	0.15	0.00039	Nutrients (63%) Electricity (34%)
	Circular	23.1	0.15	0.00039	Nutrients (63%) Electricity (34%)
SCP	*Base*	12.3	0.29	0.00027	Glucose (46%) Ammonia Nitrate (37%)
	Circular	3.4	0.06	0.00004	Heat (38%) Ammonia (35%) Electricity (10%)
Black Soldier Fly	*Base*	10.2	3.46	0.00074	Heat (62%) Biogenic inputs (38%)
	Circular	9.1	0.03	0.00037	Heat (69%) Biogenic inputs (30%)
Crickets	*Base*	0.9	0.15	0.00006	Nutrients [Gluten, oat, barley (85%)]

Beef (26% protein)	110.5	9.12	88.04000	
Fishmeal, anchovy, 63-65% protein	2.1	0.17	0.00580	

6 Discussion

The results of this work show that alternative proteins have the potential to reduce the environmental impacts from traditional protein production when compared to proteins which have a high environmental impact such as beef. However, their processes still need to develop and scale in order to improve beyond lower carbon protein sources such as fishmeal derived from anchovy. It was seen that implementing circular economy actions into these processes would serve to reduce the carbon footprint of the different case studies. However, the results of the circularity assessment, indicators, and LCA results showed that not all circularity options are made equal. Even in the early development stages, alternative proteins production processes have been shown to differ substantially, as the above descriptions highlight. Therefore, finding one-size-fits-all approach to implementing circular economy principles to the broader food system is difficult and would be of little practical use. However, applying a combined LCA and circular economy approach provides the benefits of understanding the most critical inputs and potential circular approaches to them, while simultaneously identifying outputs to be of use to other agents or which can be used repeatedly within the production process. As a result, a combined LCA and circular economy approach can improve system performance and reduce environmental impacts.

In doing so, it is beneficial to identify and utilize a set of circularity measures against which these diverse production processes can be assessed based on their environmental impacts and resource use. As Velasco-Munoz et al. (2021) highlighted, there is a need to identify specific circularity indicators for food systems, as most indicators are currently utilized to analyze efficiency improvements in relation to linear models that were adapted to circular economy principles. To address this gap, several circularity indicators were adopted in this report, namely resource, energy, and water circularity indicators. These indicators were selected because these were the most critical and yet comparable metrics which could be used to compare very different alternative protein production processes. The challenges of such indicators are associated with their calculation and data collection as methodologies, data quality and data availability may differ. This is why a paired LCA and circular economy approach is beneficial, because with the LCI requirements needed to perform the LCA, these indicators can be more easily extracted. Nonetheless, the CE approach and indicators presented in this work could be expanded to both alternative and traditional protein production in the future, thereby adding relevant and comparable insights to the literature.

While there are certainly substantial benefits to be realized through the implementation of circular economy principles within the food system, challenges exist, as noted by Borrello et al. (2016). One key challenge relates to reverse cycle logistics management as any circular design needs cost-efficient and better-quality collection and transportation systems which can be highly complex, especially if globally distributed. Related to this, as noted by Koppelmäki et al. 2021, not all circularity loops are equal. Different approaches are required at different scales, and each scale and input requires a different approach (i.e. CE approaches to electricity versus biological inputs). In terms of energy inputs, depending on the location, small food producers such as the case studies here may have low agency in terms of changing the inputs into their systems. In the EU, the Guarantee of Origin (GO) market helps allow access to renewable energy within the EU electricity market, yet this places a green premium on producers. For alternative protein producers who are still working to compete with traditional agriculture, these costs could potentially be prohibitive. Regarding material inputs, sometimes there may not be suitable circular or low-carbon alternatives, perhaps for aspects such as phosphate. While means of circular phosphate could be possible through extraction from food waste, excretion, etc., this market is currently underdeveloped and thus makes it more theoretically interesting as opposed to a business case (Neset et al. 2016). Therefore, access to critical inputs and their respective cost may provide challenges to CE integration. Other challenges are concerned with infrastructure, as e.g. water treatment facilities may not able to recover phosphate due to technical and design issues. There may also be geographical obstacles, e.g. the distance to be covered to transport a waste from a given activity to become an input somewhere else may well increase GHG emissions enough to offset any such benefits due to the CE integration (Jurgilevich et al., 2016). Yet another challenge, specific to alternative proteins which may spur innovations in CE integration into food systems, is acceptability of consumers (Borrello et al., 2016; Suman et al.; 2015). Furthermore, the technology development and the diffusion of know-how may require considerable effort and for many niche innovations, such as those analyzed in this paper, to become price-competitive, scaling of production is needed which takes time. Further challenges include, transforming traditional systems will still require some additional research and insights (e.g. the relative efficiency for insects as an alternative to traditional feed options for livestock. Additional challenges arise due to institutional structures and regulations, e.g. regulations on animal by-products limit current feed lists for insects in the EU, thereby limiting the CE potential of insects (Ojha et al., 2020).

Despite these challenges, CE integration into the food systems is of vital importance due to the many associated benefits and their magnitude. Firstly, CE integration implies resilience through diversity, as noted by the Ellen McArthur Foundation. Greater diversity in supply chains and inputs benefit economic agents due to less exposure to price volatility of commodities, such as the recent price surges in wheat due to the Ukraine war. Diversity of production means greater agricultural resilience in terms of phosphate shortages, soil degradation and other environmental issues as compared to traditional means.

Another key benefit is related to cost reduction and mutual benefits across diverse agents within the food system. For instance, inefficiencies within food systems globally are estimated to account to as much as one trillion dollars every year. These numbers mount to two trillion dollars if social and environmental costs are accounted for (FAO, 2011). CE integration can, by reducing these inefficiencies, reduce these costs to the global economy. Another key advantage of CE integration is the increased food waste utilization, which while not the focus in this work, has several environmental and social benefits. For instance, an increased rate of reuse and recovery of phosphate as a recycled fertilizer increased agricultural efficiency substantially and is key to ensure food security and resilience (Cordell et al., 2011). Another benefit to higher food waste utilization emerges in terms of reduced GHG emissions embedded in the food value chain, e.g. avoided methane emissions from landfill due to decomposition. Other environmental benefits are concerned with reduced need for land and other resources, thereby lessening the stress on the environment.

Specifically in relation to insect rearing as an alternative to traditional feed options for poultry, DiGiacomo and Leury (2019) provide a literature review on effects of insect feed as an alternative. They note that, while further research is needed to confirm the insect fed pigs' "palatability, inclusion level, growth responses, and meat quality", the effects are positive overall. The authors also highlight the safety of insect protein, which is key to the acceptability of the product. Cadinu et al. (2020) on the other hand, assessed the suitability of insect as an alternative fishmeal. Out of the three insects analyzed, either no significant difference was revealed when traditional fishmeal was replaced or positive benefits were realized (including higher growth rates, better quality flesh, anti-inflammatory responses and improved anti-parasite activity). Further research is needed to assess the suitability of algae protein as an alternative in terms of digestibility and other quality indicators. Regarding SCPs, several studies have demonstrated the suitability of SCPs as an alternative to fishmeal in aquaculture with success (Olvera-Novoa et al., 2002; Gao et al., 2008).

As previously mentioned, global nutrient imbalance is increasing as higher-income countries are accumulating nutrients and lower-income countries are increasingly experiencing nutrient deficits, resulting in lower agricultural productivity (Schoumans et al., 2015). Therefore, CE integration may be key in reversing this trend and establishing a global nutrient balance.

While this study is valuable to bridge the research gap within the circular economy literature especially relating to food systems, this work has several limitations. Firstly, there is some degree of criticism associated with the application of the theory of multilevel socio-technical transitions. This criticism concerns delineation, possibilities of cross-fertilization between regimes, and specific characteristics of niches to be able to be a platform for further development of the new technology (Genus and Coles, 2008). Another limitation more relevant refers to the differences in data quality of the four niche innovations studies. The results of an LCA are reliant on the data quality of the inputs, and thus for example in the case of cricket rearing in which all processing data beyond the rearing of the crickets could not be attained because they are performed by third parties, the quality of the results is then reduced. Lacking data can make a process seem more beneficial than it may actually be.

This work presents key policy implications for the expansion of CE integration in food systems, and potentially in wider applications. Thereby, the support of the European Union for research into the circular economy can lead to niche innovations, which will eventually support the change of the socio-technical regimes towards a more sustainable system. The results of this work may impact current policies such that niche innovation in alternative proteins should be continued in the EU, and wider, because they improve economic resilience, through increasing self-sufficiency and more diverse inputs / outputs, and environmental performance, while simultaneously support climate change (and other earth system changes) resilience. Future policies to support CE practices and sustainable food production could be aided through R&D funding (Muscio and Sisto, 2020). In addition, the EU could support the creation of a system for companies to report inputs and outputs, thereby acting as a circular economy database. This policy would add tremendous value to support CE implementation as low quality data forms one of the greatest challenges to date. Moreover, such a system might help facilitate partnerships between companies, which otherwise might not have formed due to the lack of a platform to find suitable partners.

7 Conclusions

Circular Economy development in the food sector is very often focused on minimizing or eliminating food waste with the focus on the value chain downstream from food production. It is critical to minimize or eliminate food waste, but much can be achieved further upstream both in terms innovative waste management approaches for the outputs in processing and use of circular inputs (re-used, recycled, biological and/or renewable resources) this is what the alternative protein production can achieve. For the algae production the main driver of the impacts are nutrient use and electricity consumption and thus the greatest circular potential is in the use of purchase of electricity sourced from renewable energy. The algae case study is already quite circular and not much more can be done, but if the processes was not as circular as it is the environmental impact would be significantly higher. For the single cell protein production, the main potential is in using residual biomass, internally circulating the ammonia that is used in the process and in the use of purchase of electricity sourced from renewable energy. For the black soldier fly production, the main circular economy potential is in the use of wasted fruits and vegetable, internal circular of the frass and other output biomaterial, along with the use of purchase of electricity sourced from renewable energy. For the cricket rearing process, the main potential is in the use of renewable material in packaging, in the use of purchase of electricity sourced from renewable energy and use the frass again in the process. Synthesizing the results across case studies, each case study has its unique potential to apply circular economy methods, however across case studies the use of recycled, re-used, or otherwise wasted raw material instead of virgin resources as inputs, using renewable energy sourced electricity, and increase the internal circulation of biomaterial to the extent possible would be the best ways to increase circularity and improve environmental performance. The main barriers in realizing the circular economy potential by using renewable energy in the processes is a need for a certificate of origin market, higher prices of electricity through green premiums or the need to be in an area that supplies renewable electricity. The main barrier in using more circular inputs is the need for specific nutrients and quality of the raw material, relatively small market for residual biomass and location specific, and the main barrier to increase internal circulation of biomaterial is the possible need for systems change. Concluding, the production of alternative proteins presents an opportunity to diversify protein production and reduce GHG emissions from protein production, and circular economy activities could help further improve the environmental performance of different alternative protein production. However, each method of production is different and will need to apply its own unique circular economy approach. Support from the EU can help to develop and diffuse such innovation more rapidly and in doing so aid in developing a more diverse, sustainable, and circular food system.

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