LCA OF WASTE-TO-FEED DIETS FOR LAYING HENS

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EXECUTIVE SUMMARY

The livestock sector is linked with both high demand of resources and associated environmental impacts, which are in part linked to consumption of feed, water, and land. Hence, there is currently a need for more sustainable feed sources which can help lower the impacts of livestock production (van Hal O, 2019). In parallel, the retail, food manufacturing, and hospitality industries create a large amount of food waste which is currently lost. Closed loop systems, which utilize food waste to create livestock feed ingredients, can potentially reduce global impacts of feed production and bolster food security.

Circular waste-to-feed systems are gaining significant momentum and are set to repurpose nutrients from lost and wasted foods to feed animals. Foods and nutrients unsuitable for human consumption are transformed into valuable source of energy through animal feeding. Moreover, food waste recycling with nutrient and energy recovery after processing of by-products or food waste results in significant domestic savings (van Hal O, 2019; Hamilton HA, 2015).

Feeding animals with food waste is an age-old practice that could have potential environmental benefits. With improved efficiency of animal feed production, and a large range of potential food waste possibilities however, understanding these benefits requires further work.

The present study is a life cycle assessment (LCA) of US laying hens' nutrition with incorporated feed derived from processed produce or bakery food-waste. Its goal is to identify to which degree the replacement of conventional feed ingredients in hens' diet with alternative ones derived from food waste provide environmental benefits.

For this, a total of nine alternative diets are examined, where the food-waste ingredient is incorporated at a 5%, 10% or 15% content per weight. The three alternative food ingredients are derived from chemically-processed grocery food waste, bakery waste and Black Soldier Fly (BSFL) meal fed with grocery waste. All diets are nutritionally equivalent to the conventional baseline diet.

Data from lifecycle inventory (LCI) databases (e.g., Ecoinvent v3.4, World Food Lifecycle Database) are used to calculate the potential environmental impact of both products, focusing on four environmental impact indicators: global warming potential, land use, water consumption and marine eutrophication. This assessment relies on the best available LCA-related information on food production and follows the ISO 14044 standard.

The overall results for the three food waste ingredients do not distinguish a clear best option among them from an environmental point of view. Instead, the results are mixed among the environmental indicators. However, bakery meal shows the lowest impact in 3 of the 4 impact categories we have focused on, whereas BSFL has the highest value in these same three categories (global warming potential, water consumption, and marine eutrophication impacts). The results for land use are in the opposite order among the three options (see Table 1).

Table 1: Lifecycle Impact Assessment (LCIA) results for 1 kg of the three food waste ingredients. Dark grey highlights indicate the highest scores for each one of the four impact categories.

Food waste ingredient	Global warming potential	Land use	Water consumption	Marine eutrophication
	kg CO_2-eq./kg diet	Points/kg diet	Liters/kg diet	g N-eq./kg diet
BSFL meal	6.74	11.35	22.04	3.56
Food waste feed	1.90	47.58	11.90	2.58
Bakery meal	0.21	58.37	1.87	2.12

When considering their use in animal diets, the results show that no diet leads to clear environmental benefits in all indicators, but rather to environmental trade-offs (Table 2). Results depend on the environmental profile of the food-waste-based ingredient together with the exact composition of each diet.

The key findings for the four main environmental indicators are as follows:

- Global warming potential: addition of bakery meal led to modest reductions in GHG emissions of the diets, up to a 5% reduction. In contrast, GHG emissions for the diets are substantially higher for food waste feed and BSFL meal. BSFL meal at 15% shows the largest increase of 350% when compared against the baseline.

- Land use: all alternative diets have the potential to reduce this impact in comparison to the baseline. The increased food replacement content facilitates the decrease in this impact, due to a reduction of agriculturally sourced feed ingredients such as soybean meal and animal/vegetable fat by food-waste-based ingredients. Between 0.06 and 0.45 m2a or 4%-51% of occupied land (BSFL diet – 15%) can be saved annually with the incorporation of food-waste ingredients.

- Water consumption: only diets with bakery meal led to moderate savings compared to baseline nutrition, around 3% reduction. All other diets lead to a higher impact when compared against the baseline diet.

- Marine eutrophication: all alternative diets, but BSFL meal at 15%, can lead to lower nitrogen emissions when compared to the baseline diet. Replacing agricultural products such as corn, soybean meal, and animal/vegetable fat leads to decreased nitrogen emissions from fertilizer use, a reduction which is more significant than nitrogen emissions occurring during the production of food waste ingredients.

- Land Use Change (LUC): for diets of the same type, increasing the food-waste ingredient in the diet aligns with a decrease in LUC and respective GHG emissions. This study shows that we reduce LUC when using the alternative diets, and even contribute to higher savings with incorporating food-waste ingredients at higher rates.

Table 2: Normalized LCIA results for layer hen diets. Values show the ratio between each diet and the Baseline diet for each indicator (100%=Baseline value). Red shaded cells indicate values that are higher than the baseline, while blue shaded cells indicate values lower than the baseline; darker shade of each color represents larger differences against.

Diet	Inclusion level of food waste ingredient	Global warming potential	Land use	Water consumption	Marine eutrophication
Baseline	-	100%	100%	100%	100%
BSFL meal	5%	179%	86%	108%	98%
	10%	265%	73%	123%	100%
	15%	350%	66%	138%	102%
Food waste feed	5%	116%	90%	102%	94%
	10%	131%	79%	104%	88%
	15%	151%	68%	112%	85%
Bakery meal	5%	97%	96%	97%	96%
	10%	95%	92%	96%	93%
	15%	99%	92%	97%	90%

A sensitivity analysis shows that using food instead of food waste would lead to no benefits in any diet. Elevating the cut-off criterion for the production impacts of grocery and bakery products increases the GHG emissions of the per-kg production of the food replacements, and subsequently the overall carbon footprint of alternative diets at 15-85%. All other indicators are also increased.

Using electricity from renewable solar power for food-waste-based ingredients production can help reduce their GHG emissions and lower the carbon footprint of alternative diets. By using this alternative source of electricity, GHG emissions can be reduced from -1% (bakery meal diets 5% and 10%) up to -51% (BSFL meal diet – 15%) – the latter is still higher though than the baseline diet emissions. Prioritizing renewable electricity can provide for significant environmental benefits for all diets and environmental indicators, with special attention for the BSFL meal and food waste feed. This scenario also highlights that under baseline conditions, much of the potential benefit of re-using food waste in these applications is being offset by the impact of electricity use and production.

In summary, these findings indicate that the use of food waste as feed for laying hens in the US has the potential for only modest environmental improvement, while carrying risks of significantly higher environmental impact. As a major amount of food waste alternatives impact is related to energy use, the outcomes of food waste as a feed ingredient can be improved using renewable energy during its production. Given the interest in establishing routes such as poultry feed as a positive end use of wasted human food products, the finding here suggests that emphasis should be kept on preventing food waste wherever possible as a top priority. These findings also suggest that new uses of food waste should be assessed in a case-by-case scenario to avoid unexpected environmental consequences. If pursuing food waste as a feed based on the current technologies here, use of renewable energy and other efforts to minimize environmental impact are needed to consider this a positive environmental outcome.

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ABBREVIATIONS AND ACRONYMS

BSFL	Black Soldier Fly Larvae
CO_2	Carbon Dioxide
EOL	End of Life
eq	equivalents
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
m2a	Unit use to measure land occupation in square meters per year
MJ	Megajoule = 1,000,000 joules, (948 Btu)
UNM	University of Minnesota
Pt	Unit use to measure land occupation[1]
US	United States
WFLDB	World Food Life Cycle Assessment Database
WWF	World Wildlife Fund

[1] See appendix I for a detailed description

1. Introduction

Heightened concern around the environmental and social sustainability of society's consumption habits has focused attention on understanding and proactively managing the potential environmental and societal consequences of production and consumption of products and services. Nearly all major product manufacturers now consider environmental and social impacts as a key decision point in material selection, and sustainability is a recognized point of competition in many industries, including food and agriculture.

The livestock sector is linked with both high demand of resources and associated environmental impacts, which are in part linked to consumption of feed, water, and land. Hence, there is currently a need for more sustainable feed sources which can help lower the impacts of livestock production (van Hal O, 2019). In parallel, the retail, food manufacturing, and hospitality industries create a large amount of food waste which is currently lost. Investigating options for closed loop systems, which utilize food waste to create livestock feed ingredients, help reduce global impacts of feed production and bolster food security.

Investments into circular waste-to-feed systems are gaining significant momentum and are set to repurpose nutrients from lost and wasted foods to feed animals. Foods and nutrients unsuitable for human consumption are transformed into valuable source of energy through animal feeding. Moreover, food waste recycling with nutrient and energy recovery after processing of by-products or food waste results in significant monetary savings (van Hal O, 2019; Hamilton HA, 2015).

Feeding animals with food waste is an age-old practice that could have potential environmental benefits. With improved efficiency of animal feed production, and a large range of potential food waste possibilities however, understanding these benefits requires further work.

A leading tool for assessing environmental performance is life cycle assessment (LCA), a method defined by the International Organization for Standardization (ISO) 14040-14044 standards (ISO 2006a; ISO 2006b). LCA is an internationally recognized approach that evaluates the relative potential environmental and human health impacts of products and services throughout their life cycle, beginning with raw material extraction and including all aspects of transportation, manufacturing, use, and end-of-life treatment. It is important to note that LCA does not exactly quantify the real impacts of a product or service due to data availability and modelling challenges. However, it allows one to estimate and understand the potential environmental impacts which a system might cause over its typical life cycle, by quantifying (within the current scientific limitations) the likely emissions produced, and resources consumed. Hence, environmental impacts calculated through LCA should not be interpreted as absolute, but rather relative values within the framework of the study. Ultimately, this is not a limitation of the methodology, since LCA is generally used to compare different systems performing the same function, where it is the relative differences in environmental impacts which are key for identifying the solution which performs best.

Among other uses, LCA can identify opportunities to improve the environmental performance of products, inform decision-making, and support marketing, communication, and educational efforts. The importance of the life cycle view in sustainability decision-making is sufficiently strong that over the past several decades it has become the principal approach to evaluate a broad range of environmental problems, identify social risks and to help make decisions within the complex arena of socio-environmental sustainability.

By LCA, the World Wildlife Fund (WWF), a leading NGO for the protection of wildlife and the environment, is leading a research project in order to examine the scalability and the environmental impacts of the incorporation of food waste ingredients that come from food manufacturing and retail into laying hen diets. To begin collecting this foundational knowledge on the related environmental implications, WWF has commissioned Quantis to perform a life cycle assessment of a baseline diet for laying hens comprised of novel food waste ingredients, manufactured from grocery food waste, by-products from bakeries and black soldier fly larvae which is fed with food waste ingredients. It is the intention that this LCA follows the International Organization for Standardization (ISO) 14040 and 14044 standards (ISO 2006a; ISO 2006b). The study has will be reviewed by the advisory group of WWF and is intended to be used for internal communication purposes and strategy by the organization, and an edited version is expected to be made public later.

2. Goal of the study

This section describes the goal and scope of the study, along with the methodological framework of the LCA. It includes the objectives of the study, a description of the product function and product system, the system boundaries, data sources, and methodological framework. This section also outlines the requirements for data quality as well as review of the analysis.

2.1. Objectives

The present study aims at understanding the environmental performance of three food-waste-to-feed technologies for egg production. The three waste-to-feed ingredients that are part of the research are:

1. Food waste from retail outlets fed to Black Soldier Fly larvae (BSFL) which are processed into a meal fed to laying hens.
2. Food waste from retail outlets treated with special enzymes that turn it into a feed ingredient for laying hens.
3. Bakery by-products processed into feed ingredient for laying hens.

The specific goals of this study are as follows:

I. Carry out a Life Cycle Assessment (LCA) following the procedures or protocols of the ISO 14040/14044 to evaluate three alternative feed ingredients for laying hens diets.
II. Compare these diets to a baseline laying hens diet.
III. Identity environmental hotspots of the alternative ingredients and identify potential benefits that the alternative ingredients may bring to the conventional diet.
IV. Explore key data points, uncertainties and methodological choices that might influence results.

2.2. Intended audiences

The project report is intended to provide results in a clear and useful manner to inform WWF of the environmental performance of alternative laying hens diets. The report and results are meant for internal communication within the WWF research project working group. A modified version of this report and the outcomes will be made public by the WWF. The level and quality of support for the conclusions will be evaluated during the review to ensure that the results are appropriate to support an internal disclosure of the LCA findings.

2.3. Disclosures and declarations

WWF seeks to evaluate and compare the environmental performance of food-waste-to-feed pathways for egg production. The project follows the ISO 14040 and 14044 standards and includes a review by the advisory group of WWF. The results of the study are intended to be disclosed to the public, as a source of information on the overall alignment with the environmental goals of WWF's research project.

3. Scope of the study

3.1. General description of the studied systems

The study focuses on the evaluation of laying hens diets to produce eggs in the US with the incorporation of food waste ingredients. The main egg production zones that are considered in the present study are Iowa, Ohio and Pennsylvania. Three food-waste ingredients are examined, namely a Bakery Byproduct Meal, a food waste Feed, and a Black Soldier Fly larvae meal. For each type of diet, formulations of 5%, 10% and 15% food-waste-based feed content are studied. All diets are compared with a baseline diet, which represents the conventional feed scenario for laying hens in the US.

The scope of the studied system is to evaluate all inputs and outputs (agricultural products, processing energy, processing water, chemicals, transportation) related with the production of a complete diet that is appropriate for eggs production in the US. Figure 2 illustrates the overall scope and system boundary of the studied system, together with the inputs and outputs that are taken into consideration.

Data on the diet compositions and nutritional properties are provided by Professor Paul H. Patterson from the Pennsylvania State University. The nutritional profile of all feed ingredients was taken into consideration when designing the diets, which are iso-caloric and iso-nitrogenous. Primary data on the manufacturing of the three food-waste ingredients are obtained from collaborative supplying companies in the US.

Land Use Change (LUC) impacts related to the production of agricultural feed products, especially corn and soybean, are also calculated in this study. Quantitative impacts are presented as well as a semi-quantitative discussion of the effects of direct land use change of produced feed ingredients in the mid-west zone of the US. This focus is made as this is a geographical zone which is normally expected to feed the poultry systems under examination according to the LUC experts associated with the working group of the study.

3.2. System characterization and data sources

The present section presents the detailed description of the three food-waste manufacturing lines. The 10 examined diets are presented in Table 3.

3.2.1. Diets

The list of examined diets includes one baseline and three diets with 5%, 10% and 15% content of each of the three food waste ingredients, for a total of 10 diets. The baseline diet represents a conventional nutrition profile for eggs production in the US for the production regions. With 85.6% dry matter content, it provides around 2,833 kcal/kg with a crude protein content of 16.5%. All alternative diets are designed to be nutritionally equivalent to the baseline. A complete nutritional profile of the 10 diets is shown in Appendix 7.9.

Table 3: Composition of the 10 diets

Composition of diets (% inclusion of ingredient in 1 kg diet)										
		Black Soldier Fly Larvae meal			Food waste feed			Bakery byproduct meal		
	Baseline	5%	10%	15%	5%	10%	15%	5%	10%	15%
Corn	54.1	55.8	57.4	61.7	53.3	52.5	50.4	50.1	46.1	45.0
Soybean meal	19.9	14.6	9.3	6.6	16.9	13.9	9.9	19.2	18.5	19.7
DDGS	10.0	10.0	10.0	5.0	10.0	10.0	12.0	10.0	10.0	5.1
Calcium Chips	6.2	6.0	6.0	5.6	6.1	6.1	5.8	6.2	6.2	6.2
Limestone	4.0	3.9	3.5	3.5	4.0	4.0	4.2	4.0	4.0	3.9
Animal/Vegetable fat	3.2	2.3	1.4	0.3	2.1	0.9	0	3.0	2.7	2.0
Phosphate source	1.4	1.3	1.1	1.0	1.4	1.4	1.3	1.4	1.4	1.5
Vitamins	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Salt	0.4	0.3	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3
Methionine (amino acid)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.6
Biolysine (amino acid)	0.1	0.2	0.2	0.2	0.2	0.3	0.5	0.2	0.2	0.2
Avizyme (enzyme)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Phytase (enzyme)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Bakery byproduct meal	-	-	-	-	-	-	-	5	10	15
Food waste feed	-	-	-	-	5	10	15	-	-	-
BSFL meal	-	5	10	15	-	-	-	-	-	-
Dry matter (%)	85.6	86.8	87.9	89.3	86.6	87.6	88.5	86.0	86.5	87.3
Metabolizable energy (kcal/kg)	2,833	2,833	2,833	2,833	2,833	2,833	2,833	2,833	2,833	2,833
Crude protein (%)	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5

3.2.2. Alternative Ingredients

3.2.2.1. Bakery byproduct meal

Bakery byproduct meal is produced from food wastes found in shops that sell bakery products, such as bakeries and coffee shops. It is a common practice to include such bakery wastes into animal feed. Food waste from bakery manufacturers is transported to the transfer station for a first screening to ensure good quality or directly to the processing facility. Depending on the practice at the processing facility, bakery waste may be directly incorporated in the overall poultry diet without prior processing, or undergo grinding, drying and processing into a 'dehydrated bakery meal', which is later sold to feed mills. Any existing packaging waste (such as cake cups or plastic wraps) are separated and normally incinerated either at the plant for direct heat recovery or at the municipal waste treatment plant.

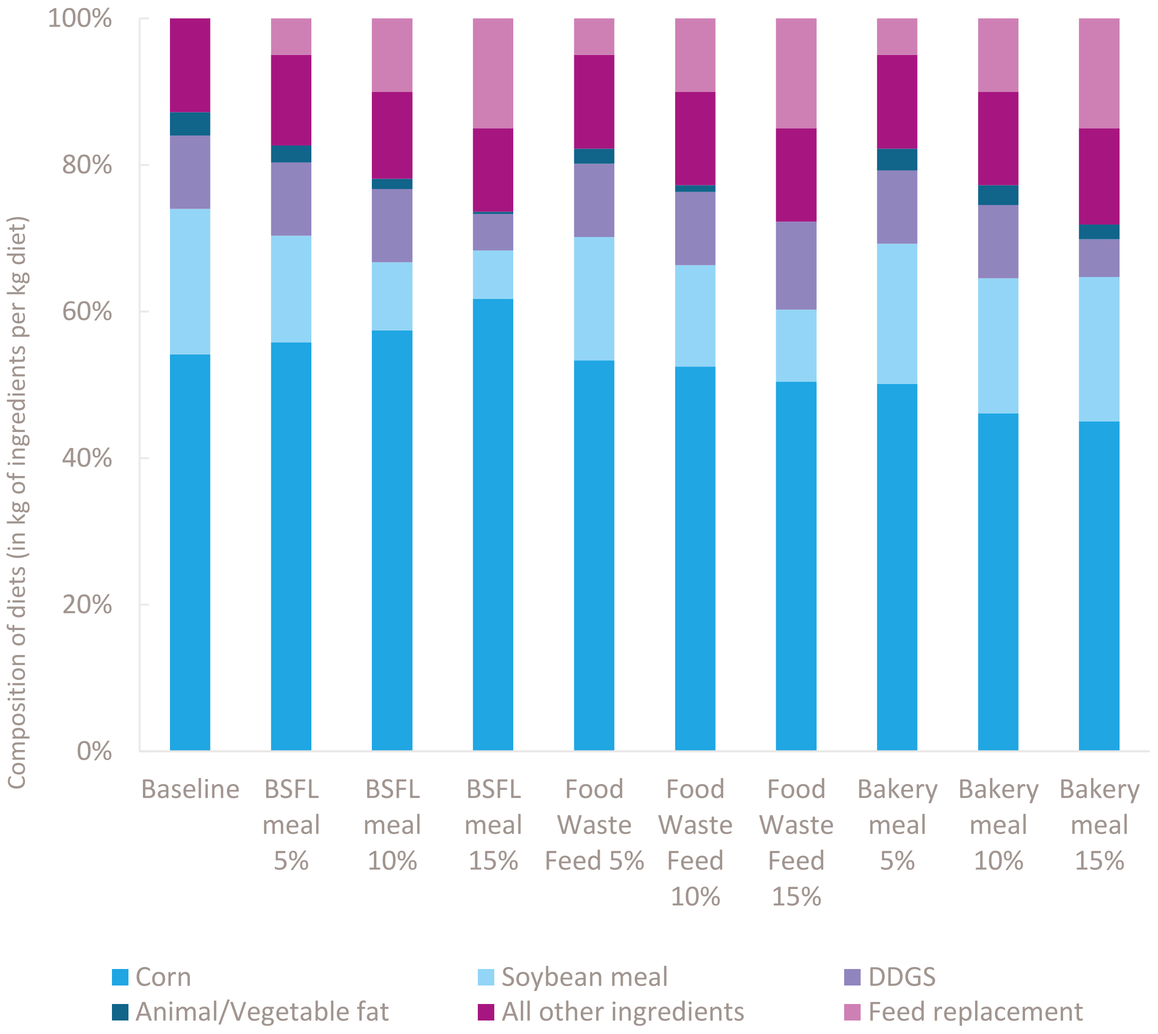

Figure 1: Feed composition of the baseline and the alternative diets

3.2.2.2. Food waste feed

Produce food waste from grocery stores is collected and undergoes chemical digestive processing. The resulting material is a sludge, which is further processed to form the final pellet. The generated process waste goes to landfill after the cleaning of the facility. This food waste feed ingredient has been proven to provide for similar nutrient content compared to corn or soybean meal rich feed for growing-finishing pigs (Jinno, He, Morash, & et al., 2018)

3.2.3. Black Soldier Fly Larvae meal

In the later years, the transformation of insects into food or feed has been gaining increasing attention. The Black Soldier Fly is one of the main insects currently tested for feed applications (van Huis, 2020). This ingredient regards the incorporation of the *Hermetia illucens*, the BSFL, as a substitute of protein source in commercially available poultry diets. BSFL is directly used as fresh biomass (puree) in a diet, or, being high in protein content, it can serve as protein meal source. In parallel, the BSFL transformation results in the co-production of larvae metabolic waste, or else frass, which can be used a rich in nutrient material for the soil. Moreover, many studies have highlighted the protein replacement potential especially about the incorporation and valorization of agri-food or other types of waste (Smetana S, 2019).

The transformation process starts with the fly feed preparation from food waste and continues with the nursery and rearing of the fly. Once reared, the larvae are dried as a preparatory step for the manufacturing of puree or meal (Smetana S, 2019). Dried BSFL produced by a US supplier is considered for the purpose of laying hens feeding, together with the co-production of larvae frass.

3.3. Function and functional unit

3.3.1. Function and functional unit

Life cycle assessment relies on a “functional unit” (FU) for comparison of alternative products that may substitute each other in fulfilling a certain function for the user or consumer. The FU describes this function in quantitative terms and serves as an anchor point of the comparison ensuring that the compared alternatives do indeed fulfil the same function. It is therefore critical that this parameter is clearly defined and measurable.

The functional unit for this study is:

1 kg of nutritionally equivalent diet for laying hens in the US.

The function of the system is to provide the **necessary nutrient-rich feed to laying hens for eggs production**.

3.3.2. Reference Flows

To fulfill the functional unit, different quantities and ingredients are required to prepare 1 kg of nutritionally equivalent diet for laying hens in the US. Those are known as reference flows. The FU of this system is necessary to provide the essential nutrients required by the laying hen to maintain herself at a high rate of egg production and egg quality. The main reference flows for the systems under study are the following:

Baseline diet: Feed ingredients combined in a baseline corn/soybean meal diet, which deliver the needed intake of protein, fat, carbohydrates, and other minerals to laying hens for egg production.

Bakery byproduct meal diet: Diets containing 5%, 10% or 15% of processed bakery byproduct meal, delivering the needed intake of protein, fat, carbohydrates, and other minerals to laying hens for egg production.

Food waste feed diet: Diets containing 5%, 10% or 15% of food waste feed from grocery store food wastes, delivering the needed intake of protein, fat, carbohydrates, and other minerals to laying hens for egg production.

Black Soldier Fly larvae meal diet: Diets containing 5%, 10% or 15% of Black Soldier Fly larvae meal made from larvae that are fed with grocery stores' food wastes, delivering the needed intake of protein, fat, carbohydrates, and other minerals to laying hens for egg production.

3.4. System boundaries

The system boundaries identify the life cycle stages, processes, and flows considered in the LCA and should include all activities relevant to attaining the above-mentioned study objectives. The following paragraphs present a general description of the system as well as temporal and geographical boundaries of this study.

The system boundary of the study is aligned with the recommendations in the Product Environmental Footprint Category Rule (PEFCR) on Feed for Food Producing Animals, except for feed production life cycle step (else, mixing of feed ingredients into one uniform final product), which is left out of scope due to lack of primary data and as this activity is considered to be identical across the 10 diets.

3.4.1. General system description

This study assesses the life cycle of feed for eggs production from the extraction and processing of all feed ingredients, with exclusion of feed milling, till they are ready to be fed to laying hens, including transportation activities along the value chain (Figure 1).

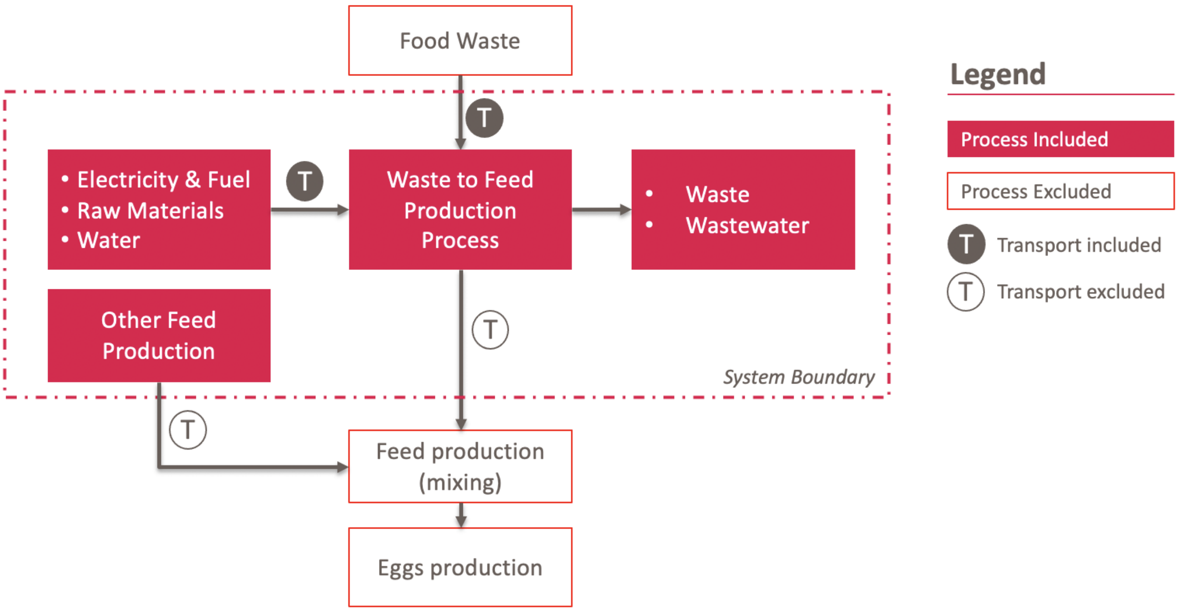

*Figure 2: **System boundary of diet production for** laying hens*

As is generally done in LCA, within the above shown steps, the assessment considers all identifiable "upstream" activities to provide a view as comprehensive as possible of the product's cradle-to-gate life cycle. For example, when considering the environmental impact of transportation, not only are the emissions of the truck or ship considered, but also included are the impacts of additional processes and inputs needed to produce the fuel and the vehicle. In this way, the production chains of all inputs are traced back to the original extraction of raw materials. The scope of the evaluated system ends at the feed production site.

Capital goods, as agricultural machinery or buildings used in the product's manufacture, are included wherever data was available. Capital goods are not included for distribution. For the purposes of this analysis, the system was grouped into the following principal life cycle stages.

1) Production of food-waste ingredients
2) Other feed production
3) Feed processing

3.4.2. Temporal and geographic boundaries

This LCA is representative of eggs produced and sold in the US at the time the study is conducted (2019-2020). Egg production is especially examined for Iowa, Ohio and Pennsylvania. Data and assumptions are intended to reflect current equipment, processes, and market conditions. Data has been selected where possible to best match these geographic and temporal conditions, although data from the relevant geography is not always available and data for most aspects of the system are at minimum a year old and in many cases several years old.

Most of the activities that are included in the system boundaries take place in the US. It should be noted, however, that some of the feed ingredients are sourced from the global market and might, hence, take place anywhere or anytime. For example, the processes associated with the supply of agricultural feed products take place in the mid-west area of the US, and the food-waste sourcing and processing are happening in the broader US geography. In addition, certain processes may generate emissions over a longer period than the reference year. This applies to landfilling, which causes emissions (biogas and leachate) over a period of time whose length (several decades to over a century/millennium) depends on the design and operation parameters of the burial cells and how the emissions are modeled in the environment.

Regarding the temporal boundaries of the study, those are aligned with the temporal scope of the study as primary data is being collected for the current or previous year. Literature information is chosen from research articles which date no further back than 2015.

3.4.3. Cut-off criteria

Processes may be excluded if their contributions to the total system's environmental impact are less than 1%. Materials that are less than 1% by mass are assumed to also contribute less than 1% of the environmental impact, except in cases where there is a reason to expect otherwise, such as with hazardous substances. Despite this criterion for allowing components to be excluded, all product components and production processes are included when the necessary information is readily available, or a reasonable estimate can be made.

It should be noted that the capital equipment and infrastructure available in the Ecoinvent database v3.4 is included in the background data for this study to be as comprehensive as possible.

The food waste ingredients that are considered in this study, are ingredients which are valorized by the examined systems and which would otherwise end up to waste streams. The fact that those streams would not be sold or utilized for other types of economic activities allow us to apply a cut-off approach for their production, in other words, no impacts are allocated to food waste. This is relevant to grocery store waste, bakery waste and food waste used as feed in the BSFL meal supply chain. Note that processing parameters, such as energy, water, or transportation, are included, as those are specific to the evaluated manufacturing systems (Hamilton HA, 2015).

Moreover, the following processes were left out of the system boundaries, in conformity to usual practices in attributional LCA: labor and poultry feeding.

4. Assessment methodology

4.1. Allocation methodology

A common methodological decision point in LCA occurs when the system being studied is directly connected to a past or future system or produces co-products. When systems are linked in this manner, the boundaries of the system of interest must be widened to include the adjoining system, or the impacts of the linking items must be distributed—or allocated—across the systems. While there is no clear scientific consensus regarding an optimal method for handling this in all cases many possible approaches have been developed, and each may have a greater level of appropriateness in certain circumstances (Reap, 2008).

ISO 14044 prioritizes the methodologies related to applying allocation. It is best to avoid allocation through system subdivision or expansion. If that is not possible, then one should perform allocation using an underlying physical relationship. If using a physical relationship is not possible or does not makes sense, then one can use another relationship.

In alignment with the cut-off allocation approach for addressing systems that donate or receive material or energy source from an upstream or downstream system, applied in the foreground modeling described above, the Ecoinvent life cycle inventory system model chosen to apply in this study is that called cutoff by classification. This approach is explained in detail on the Ecoinvent website and in an Ecoinvent v3 overview and methodology paper (Wernet, et al., 2016). In summary, the burdens of producing primary materials are always assigned to the first user of those materials, and recyclable materials are burden- and credit-free to those users.

Ecoinvent 3.4 typically uses economic allocation for multi-product systems. World Food LCA Database (WFLDB) (see section4.2 for further description) also uses economic allocation for multi-product systems, except when stated otherwise, as in the case of dairy system where it follows International Dairy Federation allocation guidelines. The economic allocation principle is used for crop co-products, animal feed, and animal co-products specifically and agricultural production systems in general and has been widely used for these products (Bengoa, Rossi, & Mouron, 2017; Dettling, Tu, Faist, DelDuce, & Mandlebaum, 2016; Wiedemann, et al., 2015). Many of the processes in the Ecoinvent database also provide multiple functions, and allocation is required to provide inventory data per function. This study consistently uses the allocation method used by Ecoinvent 3.4 in its cutoff by classification approach and the allocation used by WFLDB as previously described. Most products in this category are allocated on a revenue basis. Economic allocation is one of the widely used allocation method for multi-output agricultural systems, as it addresses the main driver for these production systems, being revenue and demand. The choice of allocation metric and factors can be highly influential to the resulting environmental indicator impact of each product.

4.1.1.Transportation

Transportation vehicles have both a weight capacity and a volume capacity. These are important aspects to consider when allocating the impacts of an entire transportation journey to one product. Vehicles transporting products with a high density (high mass-per-volume ratio) will reach their weight capacity before reaching their volume capacity. Vehicles transporting products with a low density (low mass-per-volume ratio) will reach their volume capacity before reaching their weight capacity. Therefore, the density of the product is critical for determining whether to model transportation as volume-limited or weight-limited.

In this study, all transportation is assumed to be weight-limited and the transportation of the cargo within the vehicle is therefore allocated based on its weight.

Following the Feed PEFCR, transportation by truck for distances up to 100 km was modeled using EURO3 3.5-7.5 ton truck, and above 100km using >32 ton EURO 4 truck.

4.1.2. Ecoinvent processes with allocation

Many of the processes in the Ecoinvent database also provide multiple functions, and allocation is required to provide inventory data per function or per process (Weidema, 2013). This study accepts the allocation method used by this database for those processes. It should be noted that the allocation methods used in Ecoinvent for the background system (i.e., upstream activities for which generic information is used in the model, such as production of energy and raw materials or emissions from transportation), such as mass or economic allocation, may be inconsistent with the approaches used to model the foreground (i.e., modelled specifically for this study) system. Continuation of a single allocation methodology into the background datasets would add substantial complexity without necessarily improving the quality of the study (i.e., ISO does not require that all multi-output processes are handled with the same allocation methodology). The allocation methodology used in the background datasets is considered appropriate to the context of those processes.

4.2. Life cycle inventory

The quality of LCA results is dependent on the quality of data used in the LCA model. Every effort has been made for this investigation to implement the most credible and representative information available.

The inventory of the study is aligned with the recommendations in the PEFCR on Feed for Food Producing Animals. As the with the feed production life cycle step (else, mixing of feed ingredients into one uniform final product) is left out of scope in this study (see System Boundary), no primary data are acquired regarding the energy consumption in feed mill operations and outbound transport to the animal farm. Those activities are in general considered to be identical across the 10 diets.

4.2.1. Primary and secondary data

Life cycle inventory (LCI) data collection mainly concerns the materials used, the energy consumed, and the wastes and emissions generated by each process included in the system boundaries. Primary data on the examined poultry diets have been collected directly by the WWF working group, and especially by Prof. Paul H. Patterson from the Pennsylvania State University. Other data on the preparation of food-waste-based ingredients, namely bakery byproduct meal, food waste feed, and black soldier fly larvae meal, are obtained from collaborative supplying companies in the US who operate in the different sectors of food waste ingredients used in laying hens' diets.

Most secondary life cycle inventory data sources come from the *Ecoinvent* database v3.4 in the cut-off by classification allocation model (Weidema, 2013). Ecoinvent is recognized as one of the most complete background LCI databases available, from a quantitative (number of included processes) and a qualitative (quality of the validation processes, data completeness, etc.) perspective. Historically focused on European production activities, it has reached a global coverage of thousands of commodities and industrial processes. It is believed that the credibility and transparency of this database make it a preferable option for representing North American conditions. The data's geographic representativeness is one aspect evaluated as part of the data quality assessment.

Some agricultural products are modeled using secondary data from the World Food LCA Database (WFLDB). For a full description of the methodology and modeling hypotheses within the WFLDB, please refer to the WFLDB Methodological Guidelines v3.5 (Nemecek, 2019).

Table 4: Main data sources and assumptions for the bill of activities

	Diet ingredients	Bakery meal	Food waste feed	BSFL meal
Data sources	WWF provided all primary information regarding the composition of the 10 diets.	Suppliers 1 & 2 provided all primary information.	Supplier 3 provided all primary information.	Supplier 4 provided all primary information.
Assumptions	1.Agricultural and processed food ingredients are represented by the closest dataset available (Table 5). 2.Animal/vegetable fat is modeled as a 50% beef fat-50% rapeseed oil fat source, with available Ecoinvent datasets	Cut-off for packaging of bakery products. Only impacts from end-of-life treatment are allocated to the bakery meal system. No valorization benefits (from incineration) are considered for the bakery meal system.	No assumptions made.	No assumptions made.

Table 5 describes the datasets that are used to translate the feed inputs into environmental emissions. In case where proxy secondary data are considered due to lack of other primary data on the specific ingredient's manufacturing, those are also described.

Table 5: Dataset proxies for diet ingredients

Feed Ingredient	Secondary data description
Corn	Non-irrigated maize production in the US
Soybean meal	Soybean meal produced in the US
DDGS	Distiller's Dried Grains with Solubles, from maize grain ethanol production in the US
Calcium Chips	Ca chips are a form of limestone with about 38% calcium. Modeled with limestone as proxy
Limestone	Global market of limestone production
Animal/Vegetable fat	A blended animal/vegetable fat source. Modeled as 50% US beef fat and 50% US canola oil
Phosphate source	Mineral of phosphorous and calcium, modeled as an average inorganic chemical as proxy
Vitamins	Global market of organic chemicals
Salt	Global market of sodium chloride powder

Methionine (amino acid)	Global market of methionine
Biolysine (amino acid)	Modeled as enzymes as a proxy, due to lack of environmental data on amino acids
Avizyme (enzyme)	Global market of enzymes
Phytase (enzyme)	Global market of enzymes

4.2.2. Bakery byproduct meal inventory

Bakery meal production is described by 2 suppliers. Supplier 1 shared information on the manufacturing process at 10 processing plants in the US with similar production lines, which are averaged to represent one manufacturing process. The survey from Supplier 2 showed three processing lines, one in Canada and two in Texas. The average of the processing inputs and outputs of the two facilities in Texas is considered leading to a total of two bakery byproduct meal production routes for Supplier 2. The manufacturing process for each of the three bakery (byproduct) meals considered are described in Table 6.

Table 6: Description of bakery byproduct meal manufacturing

Supplier	Processing plant	Process description
Supplier 1	Average of 10 bakery waste processing facilities in the US	Packaged bakery waste is transported to the processing plant. The raw material is dried and ground and mixed with wheat middlings to produce the final bakery byproduct meal. Waste packaging and sawdust are burnt on site and heat is recovered to provide for additional energy to the production line[2].
Supplier 2-A	Bakery waste processing facility in Canada	Packaged bakery waste is transported to the processing plant. The raw material is inspected for quality, and then dried, ground and screened to produce the final bakery byproduct meal. Packaging waste is sent to incineration with recovery of electricity for the local electricity grid and heat for the local paper mill[3].
Supplier 2-B	Average of 2 bakery processing facilities in Texas	Bakery waste is transported to the processing plant where it is placed in storage bay to later get directly mixed on with other feed ingredients (grains, minerals).

The bakery feed of Supplier 2-B does not lead into the production of a bakery byproduct meal but rather represents the practice of mixing bakery waste into an animal feed mix. This inventory is left out from the core study and is examined in a comparative analysis in the Sensitivity Analysis section.

[2] The recovered energy is considered to be taken into account in the overall reported natural gas consumption. No additional energetic benefits are modeled. Only impacts from packaging and sawdust incineration are included in the LCA model.

[3] The burdens/benefits of the bakery waste treatment are considered to be attributed to the bakery production system, given that they exit the bakery meal system boundaries (energy recovery for the local community). No treatment of the packaging waste is included in the LCA model.

4.2.3. Food waste feed

Data were provided by a US supplier (Supplier 3). Produce is transported from grocery stores to the supplier's facility. Production waste is around 0.1% and is sent to landfill.

Due to confidentiality reasons, the detailed process and inventory are described in the confidential Appendix 7.2, available only to the reviewers of this report.

4.2.4. Black Soldier Fly larvae meal

The BSFL meal production is described through the fabrication process that is designed by a US manufacturer (Supplier 4). Data are provided for two BSFL production pathways, one that requires a completely vegetarian diet (Treatment 1) and one with included animal protein in the diet (Treatment 2). BSFL feed includes food waste ingredients (vegetables, pulses, boneless meat, bakery materials and fruits) which are ground prior to consumption, together with a small amount of calcium supplements. In alignment with the scope of project and focus on produce waste we decided to keep Treatment 1 (vegetarian diet) as basis in the study. Nevertheless, we expect that the nutritional profile of Treatment 2 (diet containing animal products) will provide for a richer different nutritional profile of BSFL meal in protein with, potential differences in environmental impacts.

Larvae are grown under environmental conditions in trays for 8 days with the addition of water when the moisture content dropped below 50%. At the end of the growing phase, larvae and spent feedstock (frass) are separated by screening and frozen for further analysis. The overall energetic consumption during the rearing and processing of the BSFL includes all heating, dehumidification, cooling and drying that is performed during the whole life cycle of the final product. The final product is dried BSFL together with dried frass as co-product.

Economic allocation is applied for the calculation of environmental impacts of the meal, the oil and the frass based on price estimations from the supplier.

4.3. Land Use Change

Crop products in the diets are associated with Land Use Change (LUC) impacts, which are included in the scope of this study. More specifically, this is relevant for US produced corn and soybean, which are the only agricultural products in the hens' nutrition.

LUC from crop production is modelled following the WFLDB Methodological Guidelines v3.5 (Nemecek, 2019). The method is based on the Greenhouse Gas Protocol (Bhatia, Cummis, & Brown, 2011) and allows for the calculation of both direct and indirect LUC impacts. LUC impacts are quantified based on annualized, retrospective data of the last 20 years which are retrieved from FAOSTAT. Country specific land transformations per hectare are calculated based on statistical data.

In collaboration with the University of Minnesota (UNM) and University of Wisconsin, WWF has access to land transformation impacts from corn/Dried Distillers Grains and soybean meal that are harvested in the US to cover the feeding purposes of laying hens. This demand-based method considers land transformation data over the period 2008-2016 and poultry feed supply demand in 2017 to extract country-average LUC impacts for the US. This LUC impact calculation aims to link crop production patterns with places of consumption (Smith, et al., 2017; Pelton, 2019). These consumption-based LUC impacts include carbon emissions (Spawn, Lark, & Gibbs, 2019; Lark, Spawn, & Bougie, 2020) as well as direct and indirect N_2O emissions from N mineralization of converted lands.

Default GHG emissions from LUC are based on the WFDLB in this study. A discussion on how those impacts would change with the WWF and UNM approach is made in the Results section[4].

4.4. Impact assessment

4.4.1. Impact assessment method and indicators

Impact assessment classifies and combines the flows of materials, energy, and emissions into and out of each product system by the type of impact their use or release has on the environment. The method used here to evaluate environmental impact is the Environmental Footprint (EF) method (JRC-IES 2017). This method assesses 16 different potential impacts categories (midpoint). It is the result of a project for the European Commission that analyzed several life cycle impact assessment (LCIA) methodologies to reach consensus. It is the official method to be used in the Product Environmental Footprint (PEF) context of the Single Market for Green Products (SMGP) initiative (Commission, 2013/179/EU: Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations., 2013).

The present study evaluates the impact to 3 impact categories, namely Global warming potential, Water consumption and Land Use. These indicators are selected based on the scope of the study as they address the key environmental aspects linked with animal feed production. Moreover, this set of indicators allow for an overview of the results, while maintaining a simple enough list of indicators to identify and understand the main trends. In addition to those indicators, it was outlined as important to include an assessment of the Nitrogen inputs/outputs for the system, hence the indicator of Marine eutrophication has been chosen to provide an indication of this aspect. Table 7 describes the models used for each of the considered indicators.

The European Commission Joint Research Centre (JRC) classifies every impact category according to the maturity and reliability of its underlying model:

- Level I: recommended and satisfactory.
- Level II: recommended, but in need of some improvements.
- Level III: recommended, but to be applied with caution.

Models classified at Level III are likely to evolve in a near future.

The project Advisory Group outlined the interest to additionally examine the energy footprint, which is included as an additional assessment and discussed next to the Global warming potential indicator in the Results section. The EF method indicator that is applied is *Resource use, energy carriers*. Moreover, an additional test is conducted with the Nitrogen Assessment method developed by Pelletier & Leip (2013). This method quantifies the anthropogenic mobilization, flows and emissions of fixed nitrogen in

[4] The LUC Emission Factors from UNM are confidential and not disclosed in the report.

product systems with specific characterization factors for all nitrogen-containing compounds. The method and its characterization factors are applied in the SimaPro software and its outcomes are discussed next to Marine eutrophication impacts in the Results section. See Appendix 7.4 for the full list of the included nitrogen-containing substances.

Table 7: Indicators and related assessment models

Impact category or LCI indicator	Model	Unit	Source	Class
Global warming potential	Bern model – Global Warming potentials (GWP) over a 100-year time horizon	kg CO_2-eq.	IPCC, 2013	I
Land use	Soil Quality Index (based on the LANCA model)	Points (Pt)	(Beck, Bos, Wittstock, Baitz, & Sedlbauer, 2010) (Bos, Horn, Beck, Lindner, & Fischer, 2016)	III
Water consumption	AWARE 100 model	m^3 water deprived eq	(Boulay, Bare, & Benini, 2017)	III
Marine eutrophication	EUTREND model	kg N-eq.	Struijs J. et al. 2009	II

No normalization of the results against an external reference is carried out, but an internal normalization is performed presenting results on a relative basis (%) compared to the reference for each system. No weighting of the impact categories is done; they are presented individually and not as a single score, as there is no objective method by which to achieve this.

Life cycle impact assessment results present potential and not actual environmental impacts. They are relative expressions, which are not intended to predict the final impact or risk on the natural media or whether standards or safety margins are exceeded. Additionally, these categories do not cover all the environmental impacts associated with human activities. Impacts such as noise, odors, electromagnetic fields and others are not included in the present assessment. The methodological developments regarding such impacts are not sufficient to allow for their consideration within life cycle assessment.

4.5. Calculation tool

SimaPro 9.1 software, developed by PRé Consultants (www.pre.nl) was used to assist the LCA modelling and link the reference flows with the LCI database and link the LCI flows to the relevant characterization factors. The final LCI result was calculated combining foreground data (intermediate products and elementary flows) with generic datasets providing cradle-to-gate background elementary flows to create a complete inventory of the waste-to-feed systems.

4.6. Contribution analysis

In addition to the comparative assessment, a contribution analysis is performed to determine the extent to which each process modeled contributes to the overall impact of the systems under study. Lower quality data may be suitable in the case of a process whose contribution is minimal. Similarly, processes with a great influence on the study results should be characterized by high-quality information. In this study, the contribution analysis is a simple observation of the relative importance of the different processes to the overall potential impact.

4.7. Sensitivity analysis

The parameters, methodological choices and assumptions used when modeling the systems present a certain degree of uncertainty and variability. It is important to evaluate whether the choice of parameters, methods, and assumptions significantly influences the study's conclusions and to what extent the findings are dependent upon certain sets of conditions. Following the ISO 14044 standard, a series of sensitivity analyses are used to study the influence of the uncertainty and variability of modeling assumptions and data on the results and conclusions, thereby evaluating their robustness and reliability. Sensitivity analyses help in the interpretation phase to understand the uncertainty of results and identify limitations.

The following scenarios have been identified as interesting parameters to be further investigated through sensitivity analyses:

1. Using food instead of food waste for alternative ingredients production: The case where food waste ingredients such as produce and bakery waste are not coming from waste, but from primary products is examined. This implies that 100% of the impact for producing food is allocated to it, instead of 0% when using food waste. The grocery sourced food is modeled as a mix of vegetables and fruits consisting of 20% tomatoes, 20% grapes, 20% lemons, 20% potatoes and 20% apples (mass). The bakery product is modeled as a proxy of bread, and both alternative foods are modeled based on available data Ecoinvent and the WFLDB.
2. Food-waste processing electricity: Electricity consumption has proven a significant parameter especially for the BSFL meal and food waste feed environmental impact. The sensitivity of the system to the electricity mix used for food-waste ingredient manufacturing is tested (for the three ingredients), performing a sensitivity analysis where all electricity is sourced from solar power.
3. Bakery meal production method: As an additional analysis, the default bakery meal from Supplier 1 is compared to the other 2 bakery meals from Supplier 2-A and 2-B, due to its significantly different production methods.

4.8. Report Review

A review will be conducted by Advisory Board of WWF before the confirmation of the outcomes of the present study. This process checked that the study followed the stipulations set forth in the ISO 14040 and 14044 standards (ISO 2006a, 2006b).

The critical review process is carried out in several steps:

1) Goal & Scope report review (August 2020);
2) Clarification of and response to points raised by the reviewer (September 2020);
3) Full report review (January 2021);
4) Clarification of and response to points raised by the reviewer (end January)
5) Incorporation of final comments and report submission (5th February)

The reviewers' comments, as well as Quantis comments and responses to the review are presented in the final report in an Appendix.

5. Results

The following section presents the study results. The first part focuses on the environmental profiles of the three food-waste ingredients. The second part presents a more detailed analysis of the laying hens diets results. The section closes with the three sensitivity analyses.

5.1. Food waste ingredients

The overall results for the three food waste ingredients show there is not a clear better option from an environmental point of view. When compared on a per kilogram basis, the BSFL meal exhibits the lower land use potential impact, but has the highest global warming potential, water consumption, and marine eutrophication potential. Bakery meal exhibits the exact opposite results, with the largest land use potential but the lowest values in the other 3 impact categories (Table 8).

Table 8: LCIA results for 1 kg of the three food waste ingredients. Dark grey highlights indicate the highest scores for each one of the four impact categories.

Food waste ingredient	Global warming potential	Land use	Water consumption	Marine eutrophication
	kg CO_2-eq./kg diet	Pt/kg diet	L/kg diet	g N-eq./kg diet
BSFL meal	6.74	11.35	22.04	3.56
Food waste feed	1.90	47.58	11.90	2.58
Bakery meal	0.21	58.37	1.87	2.12

BSFL meal and food waste feed are more GHG intensive on a per-kg basis due to heat and electricity consumption for processing, as they need to be grounded, dried and pelletized (Figure 8**Error! Reference source not found.**). Specifically, for the BSFL meal, we note that CO_2 emissions from microbial respiration may have a substantial contribution (up to 34%) to the overall Global warming potential of the meal, and, as this aspect is not covered in the present assessment, it is listed as a limitation of the study (Parodi, 2020). The inclusion of agricultural products, such as wheat middling in the bakery meal and enzymes for food waste feed, are driving higher land use and marine eutrophication potential impacts when compared to BSFL meal.

The water consumption impact for BSLF meal is driven by the electricity production. For bakery meal, it is driven by the agricultural production of wheat middlings, and for food waste feed by enzymes manufacturing.

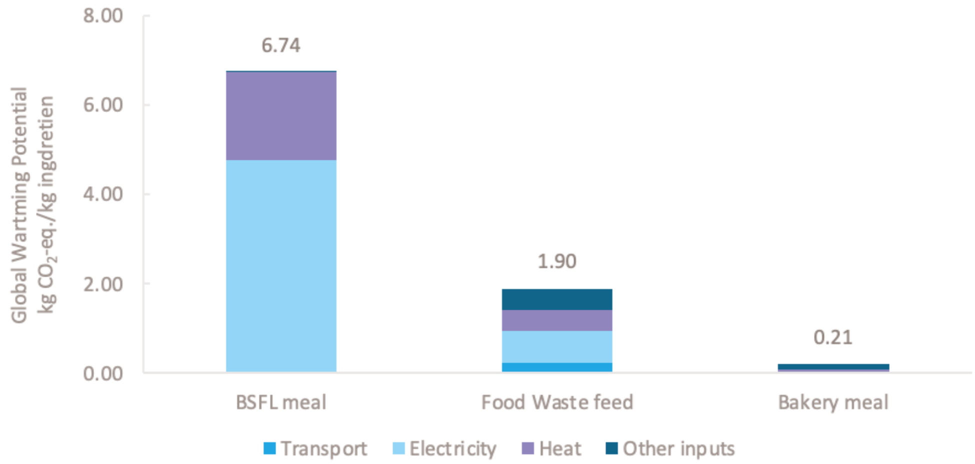

Figure 3: Global Warming Potential for the three food waste ingredients per-kg produced.

The BSFL meal is the second most intensive in GHG emissions among all feed ingredients, including standard and alternative, after enzymes. The food waste feed and bakery meal hold a comparable footprint among all ingredients, with the bakery meal being the least impacting between the two, and similar to the other agricultural products like soybean meal and corn.

Food-waste-based ingredients hold a moderate land use potential, lower than agricultural products but higher than inorganic compounds like calcium chips and limestone.

Regarding water consumption, bakery meal has one of the lowest in the feed ingredients list, while BSFL and food waste feed the impact is only lower to some of the additives (enzymes, vitamins, phosphate, methionine).

Marine eutrophication potential is moderate between when comparing alternative ingredients to traditional ones, such as soybean, DDGS and other inorganics.

Table 9: LCIA values per kg of all feed ingredients. Darker shades of red indicate higher values for each indicator. Table has been sorted by global warming potential from largest to smallest.

	LCIA values per kg of ingredient			
Diet Ingredient	**Global warming potential (kg CO_2-eq.)**	**Land use (Pt)**	**Water consumption (L)**	**Eutrophication, marine (g N-eq.)**
Enzymes	7.48	766	109.7	34.3
BSFL meal	**6.74**	**11.4**	**22.0**	**2.48**
Methionine	4.21	10.8	15.8	1.98
Phosphate source	2.17	15.7	44.3	2.03
Animal/ Vegetable fat	2.09	715	23.2	23.6
Vitamins	2.03	4.61	40.2	1.43
Food waste feed	**1.90**	**47.6**	**11.9**	**2.58**
Soybean meal	0.43	383	7.28	0.63
Salt	0.31	3.28	4.11	0.46
Corn	0.25	134	1.90	3.51
Bakery meal	**0.21**	**58**	**1.87**	**2.11**
Limestone	0.04	0.22	1.01	0.05
Calcium chips	0.04	0.22	1.01	0.05
DDGS	0.02	4.88	0.15	0.13

5.2. Laying hens diets

5.2.1. High level diets' result

Results show that all alternative diets can lead to environmental trade-offs when compared to the baseline diet. Bakery meal diets have potentially 1-10% lower environmental impacts when compared to the baseline diet in most formulations and indicators. BSFL meal and food waste feed diets show higher global warming and water consumption potential than the baseline diet, but lower land use and marine eutrophication potential; in both cases the inclusion of alternative ingredients lead to replacing ingredients like soybean meal and animal/vegetable fat, which have lower global warming or water consumption potential.

Looking at land use and marine eutrophication impact categories, all food-waste-based diets show a potential benefit when compared to the baseline, with larger benefits at increased inclusion rates of food-waste-based ingredients. Regarding land use, major benefits stem from the replacement of animal/vegetable fat and soybean meal. Marine eutrophication potential is primarily reduced for food-waste diets due to a reduced content in animal/vegetable fat. As a note, the inclusion of animal/vegetable fat in the BSFL and food waste feed diets is significantly lower to that of the baseline, whereas for the bakery meal only a small reduction is applied, nevertheless allowing benefits for the overall diets when considering a comparatively low-intensive impact of the bakery meal in these indicators.

Table 10: Normalized LCIA results for layer hen diets. Values show the ratio between each diet and the Baseline diet for each indicator (100%=Baseline value). Red shaded cells indicate values that are higher than the baseline, while blue shaded cells indicate values lower than the baseline; darker shade of each color represents larger differences against.

Diet	Inclusion level of food waste ingredient	Global warming potential	Land use	Water consumption	Marine eutrophication
Baseline	-	100%	100%	100%	100%
BSFL meal	5%	179%	86%	108%	98%
	10%	265%	73%	123%	100%
	15%	350%	66%	138%	102%
Food waste feed	5%	116%	90%	102%	94%
	10%	131%	79%	104%	88%
	15%	151%	68%	112%	85%
Bakery meal	5%	97%	96%	97%	96%
	10%	95%	92%	96%	93%
	15%	99%	92%	97%	90%

5.2.2. Contribution analysis of feed ingredients

In this section we are examining the main contributors and trade-offs for all diets and impact categories. The contributions of all agricultural products and feed replacements are shown separately, as they represent the contribution to all diets. 'All other ingredients" describes vitamins, minerals, and enzymes.

5.2.2.1. Global warming potential

None of the diets including food-waste ingredient show to lead to significant reduction in GHG emissions, with "bakery meal – 10%" showing the largest reduction of 5% and the "BSFL meal – 15%" diet showing the largest increase of 350% when compared against the baseline.

BSFL and food waste feed diets have an increased impact compared to the baseline. The replacement of ingredients with lower GHG emissions, like soybean and animal/vegetable fat, leads to an overall increased global warming potential for these formulations. The bakery meal diets follow a lower replacement of high-intensive GHG emissions ingredients (soybean, animal/vegetable fat) compared to the other two food-waste diets, and at the same time accommodate a replacement ingredient (bakery meal) with lower GHG emissions. Overall, this results in small GWP reductions compared to the baseline.

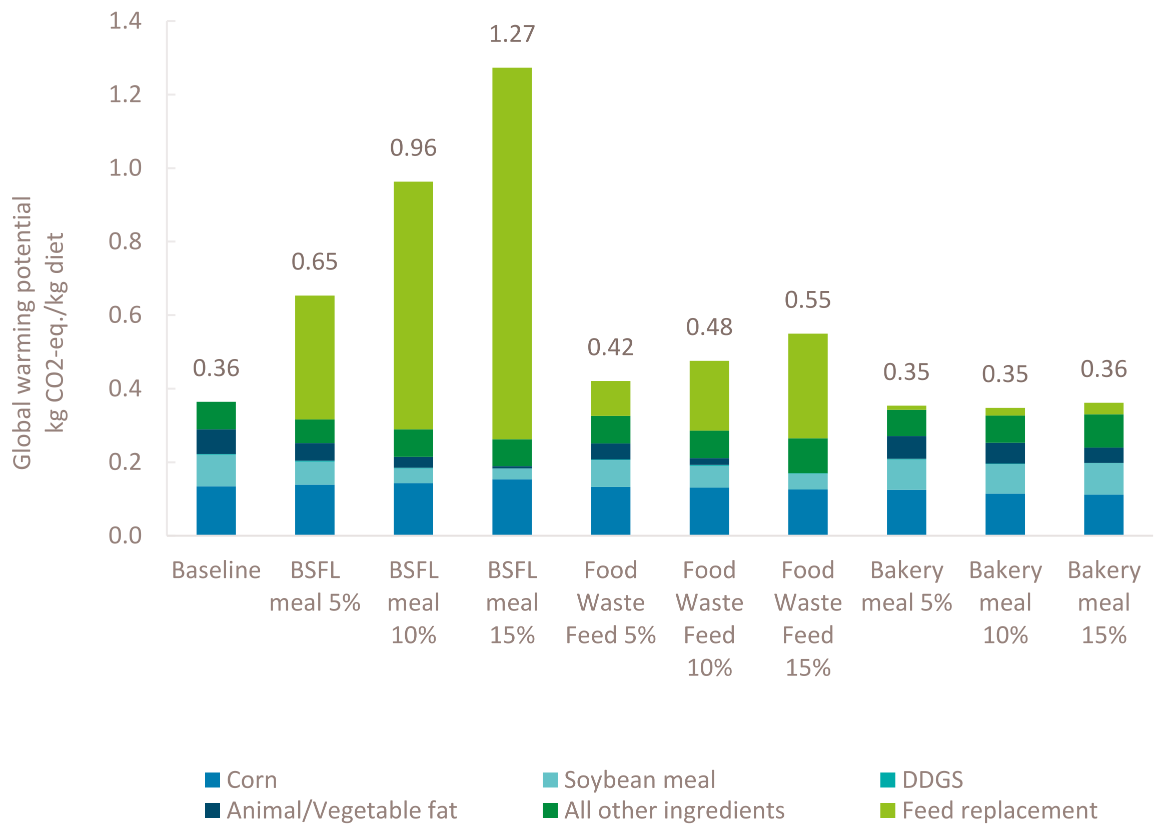

Figure 4: Global warming potential results per kilogram for baseline and alternative diets

5.2.2.2. Land use

All alternative diets have a potential benefit for land use in comparison to conventional hens' diet (Figure 5). This indicator encapsulates not just land use as a total surface used, but also includes soil health aspects like erosion and biotic production in soil. The increased food replacement content facilitates the decrease in this impact, due to a reduction of agriculturally sourced feed ingredients such as soybean meal and animal/vegetable fat which have a land use potential at least twice as large as the alternative ingredients.

Land occupation at inventory level is shown on Figure 6. It is measured in m^2 land for one year (m2a). Figure 6 shows the annual potential occupied land for crop production for the 10 diets next to the LCIA result for land use. The same trend is followed across all diets, as the crop cultivation surface is interlinked with the impact to Land use and soil occupation and quality. Between 0.06 and 0.45 m2a (4%-51%) of occupied land can be saved annually with the incorporation of food-waste ingredients (for results see Appendix 7.5).

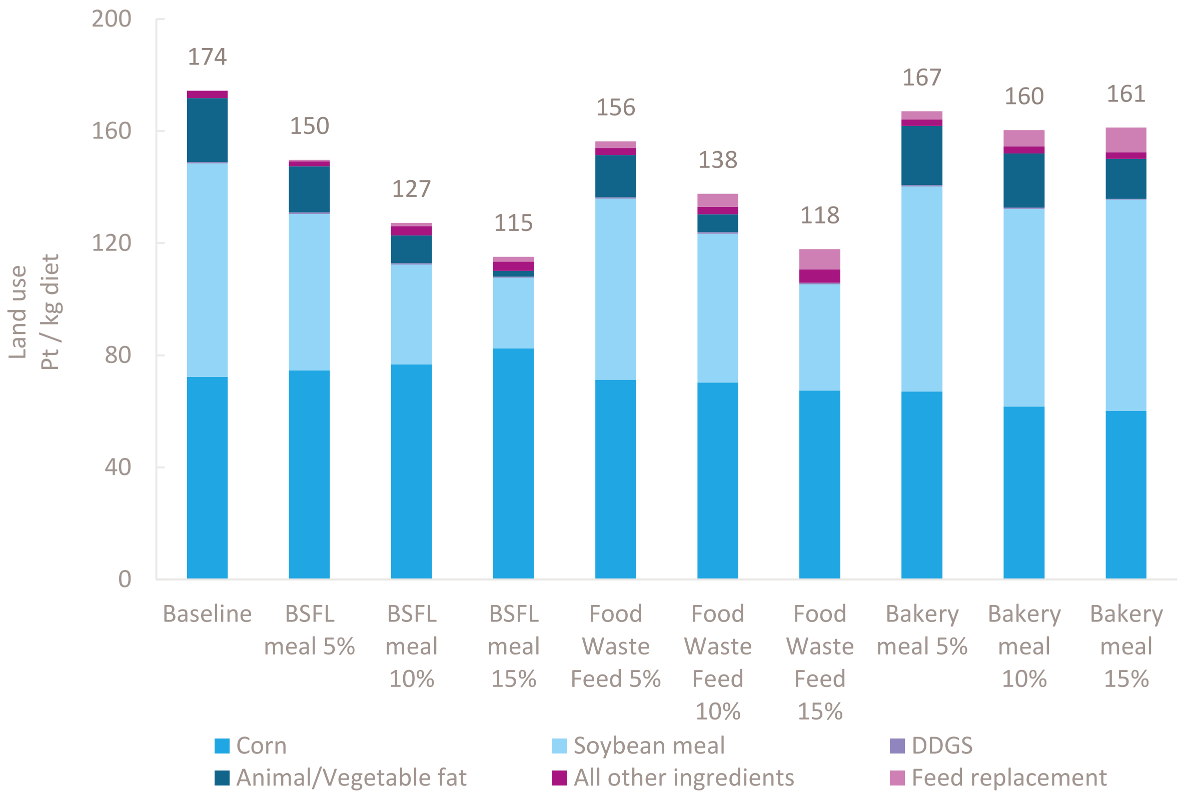

Figure 5: Land use results per kilogram for baseline and alternative diets

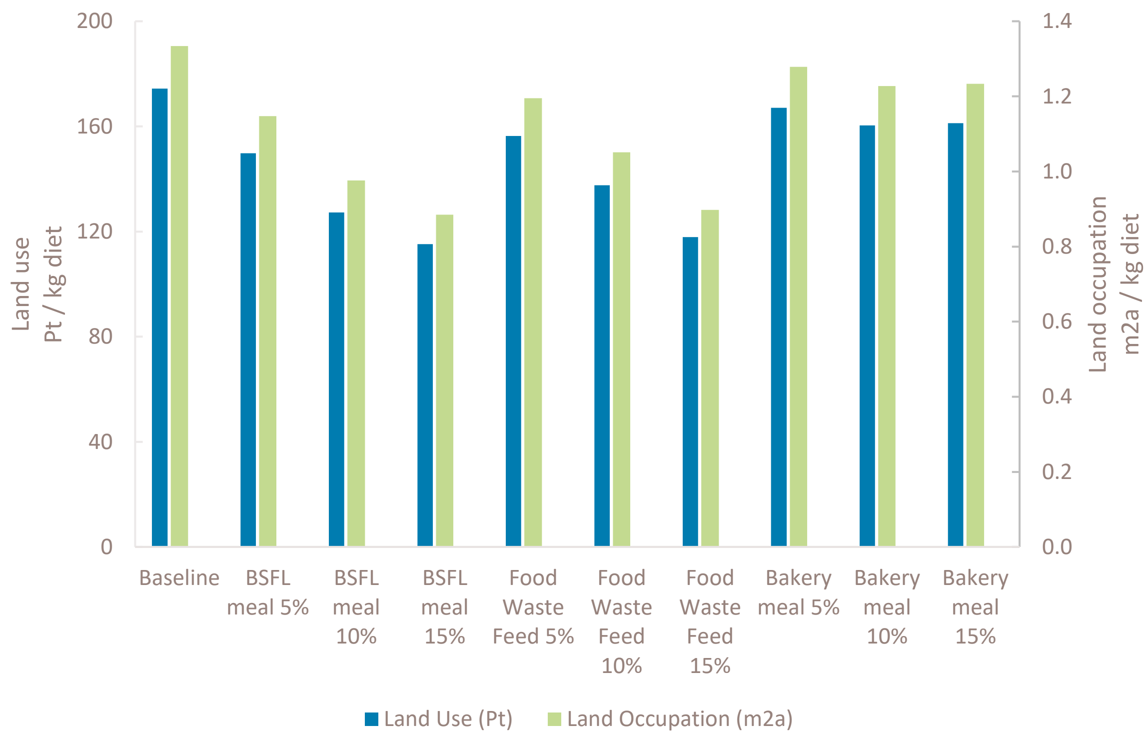

Figure 6: Land use (Pt/kg diet) and Land occupation (m2a/kg diet) for the 10 diets

5.2.2.3. Water consumption

Only bakery meal diets could lead to water consumption savings, as opposed to all other diets which lead to higher water consumption when compared against the baseline diet. For BSFL meal and food waste feed diets, the inclusion of the alternative ingredient leads to replacing ingredients with lower water consumption potential than theirs, especially for soybean meal and animal/vegetable fat, leading to an increase of 2-40% (Figure 7).

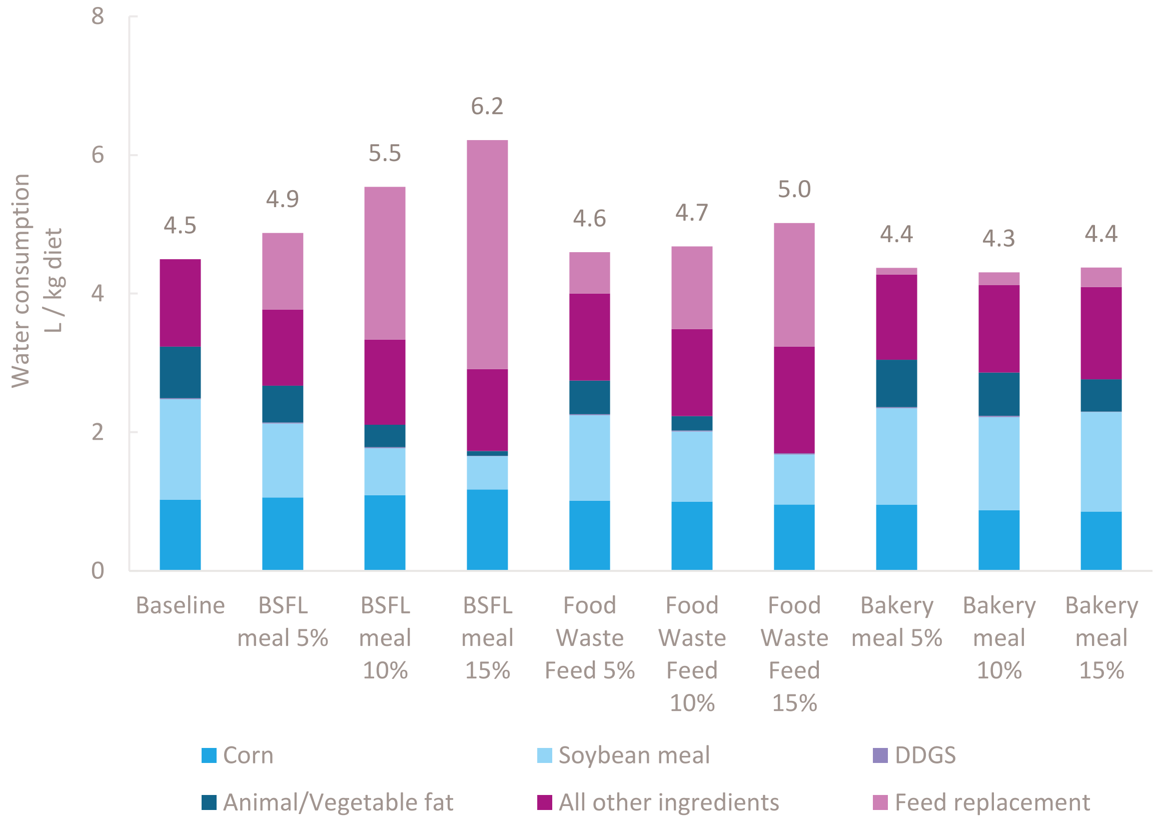

Figure 7: Contribution analysis of feed ingredients for the Water consumption indicator

5.2.2.4. Marine eutrophication

All alternative diets can lead to lower marine eutrophication potential when compared to the baseline diet, but “BSFL Meal – 15%” which leads to a 2% increase (Figure 8). Replacing agricultural products such as corn, soybean meal, and animal/vegetable fat leads to decreased nitrogen emissions from fertilizer use, a reduction which is more significant than nitrogen emissions occurring during the production of food waste ingredients.

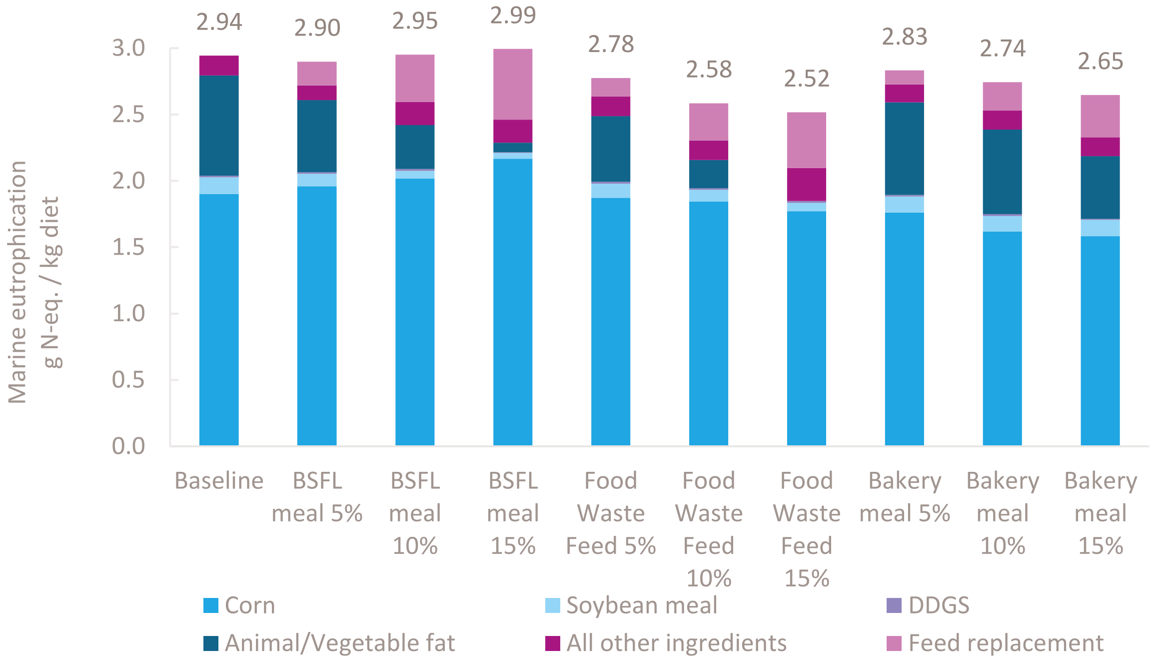

Figure 8: Contribution analysis of feed ingredients for the Marine eutrophication indicator

Nitrogen emissions are assessed using the lifecycle impact indictor marine eutrophication and by applying the Nitrogen Assessment method by Pelletier & Leip (Pelletier & Leip, 2013). Emissions from nitrogen compounds are characterized in the two methods. Similar trends in nitrogen emissions are noticed for the two assessments, with the Nitrogen Assessment showing higher impacts due to the broader coverage of nitrogen-containing substances. The list of substances covered by the Eutrophication method in kg N-eq. is shorter and focused only on elements that could lead to marine eutrophication, whereas the Nitrogen Assessment method covers a broader list of reactive nitrogen compounds, characterized in kg Nr-eq. (Appendix -Section 7.4).

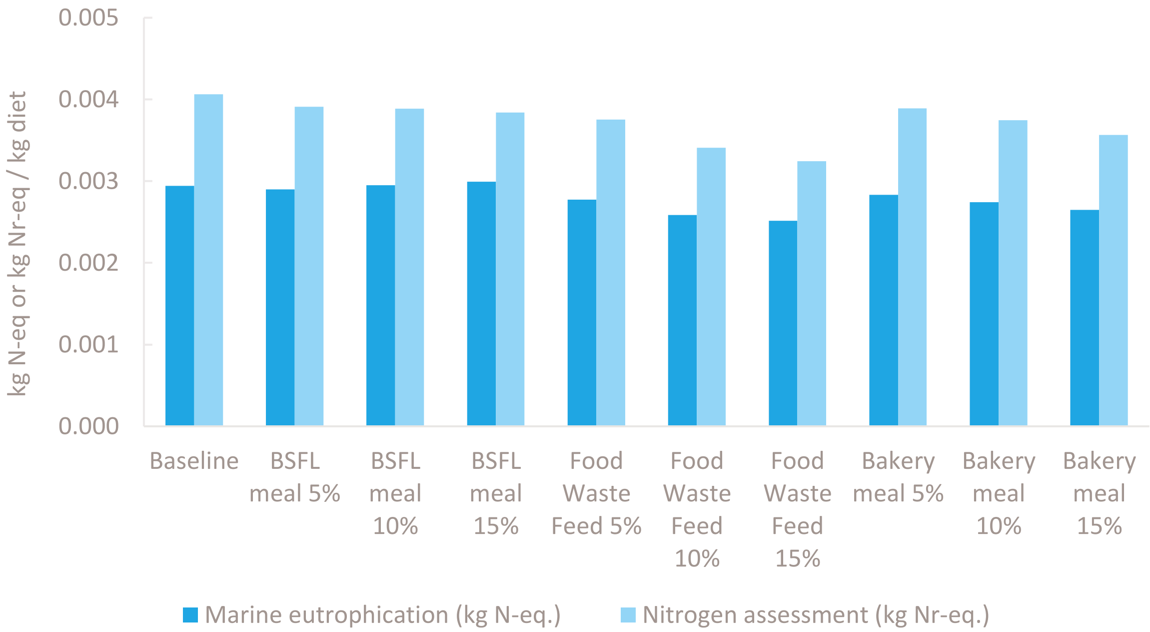

Figure 9: Impacts for the 10 diets for the indicators Nitrogen Assessment and Marine eutrophication

5.2.2.5. Resource use, energy carriers

Normally, fossil resources are correlated with GHG emissions, hence chosen to be shown in a common graph (Figure 10). For agricultural systems/products this is not always the case, nevertheless, as this study deals with high energy-intensive products (processed food-waste ingredients), common trends are noticed across the alternative diets for the two indicators. The Resource use impact for bakery meal diets is mainly driven by the manufacturing of agricultural inputs for maize production as well as enzymes and chemicals production. For food waste feed and BSFL meal diets, this impact is driven by the manufacturing of the food waste ingredient itself.

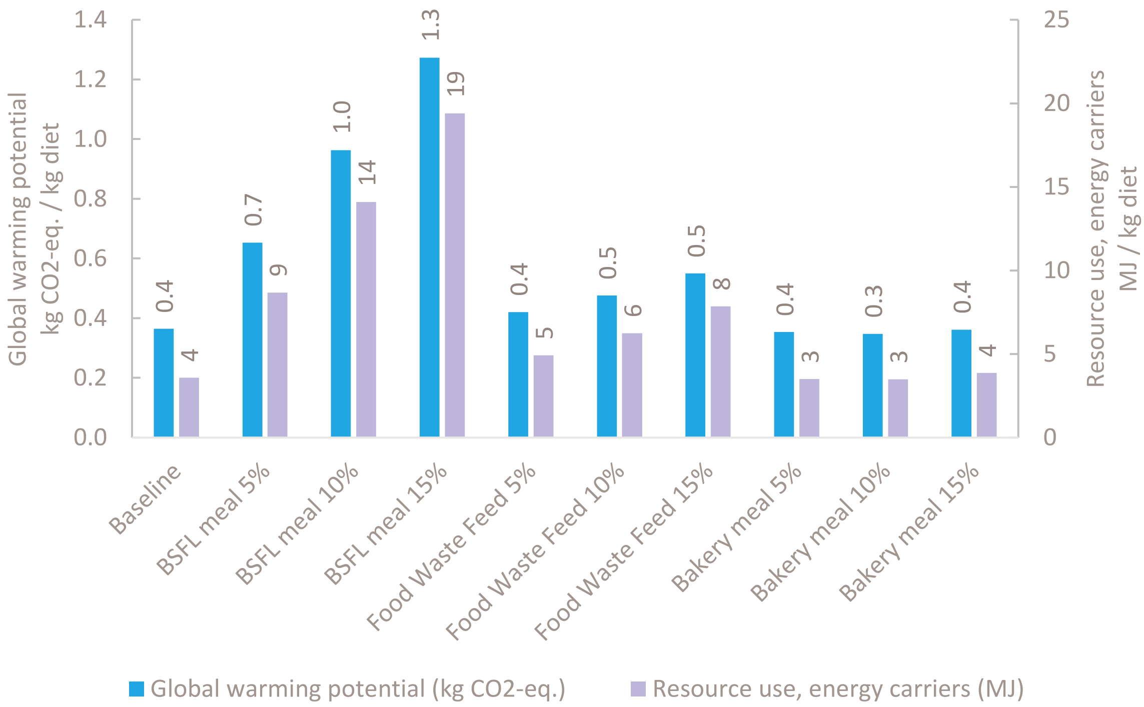

Figure 10: Impacts for the 10 diets for the indicators Mineral Resources, energy carriers and Global warming potential.

5.2.2.6. Land Use Change (LUC)

Land Use Change is examined from the inventory perspective, i.e. the transformed land (m2), and from a GHG emissions perspective (kg CO_2-eq.). Land transformation at inventory level is a measure of the change from one type of land use to another, either from forestry to agricultural land or also from one agricultural land to another (i.e., from meadow to field), measured in m^2 transformed land (Mattila, 2011). The translation of GHG emissions from transformed land is assessed at impact assessment level.

Results show that alternative diets can lead to a decrease in potential land use change and related GHG emissions when compared to the baseline. Higher inclusion rates of food-waste based ingredients lead to increased land transformation saving. A discrepancy is noticed for the bakery meal diets, where despite a decrease in LUC we notice an increase in related GHG emissions. This phenomenon is explained by the variability in the diets' compositions, especially due to the fact that land transformation quantities are not always proportional to GHG-related emissions, as emissions vary depending on the type of transformed land transformed to and from.

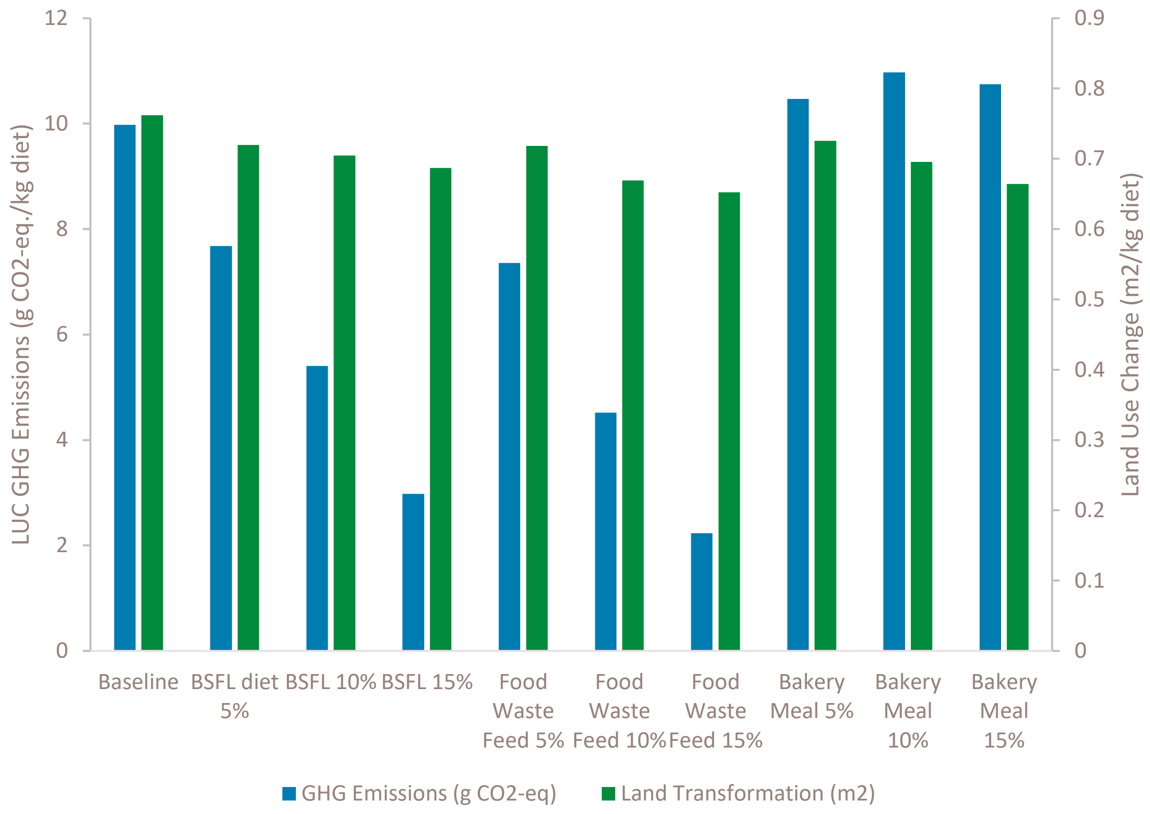

Figure 11: LUC – Global warming potential (g CO_2-eq./kg diet) and LUC – Land transformation inventory (m^2/kg diet) for the 10 diets

Land Use Change assessment is complex and sensitive to the methodological choices. Next to the default LUC approach as described in the WFLDB guidelines, the methodology developed by the University of Minnesota and University of Wisconsin is additionally examined (Figure 12). An additional assessment that focuses only on the LUC associated with the use of the three agricultural products, namely corn, soybean meal and DDGS, is performed. Results show that under this alternative methodology LUC-related GHG emissions are from 10 up to 1000 times higher per-kg of agricultural ingredient[5]. The two methods are based on different hypotheses and inventory data, and there are multiple reasons which may explain the discrepancy between the scores. Firstly, the FAOSTAT data that are used in the WFDLB are identified to represent a less recent source of land occupation and transformation data in the US, compared to the data used by the University of Wisconsin (Lark, Spawn, & Bougie, 2020). Moreover, the WFLDB method reports annualized average emissions over a 20-year period, as opposed to the UNM approach which accounts for the total emitted carbon over the considered time span.

[5] The LUC Emission Factors and scores from UNM and UW are confidential and not disclosed in the report.

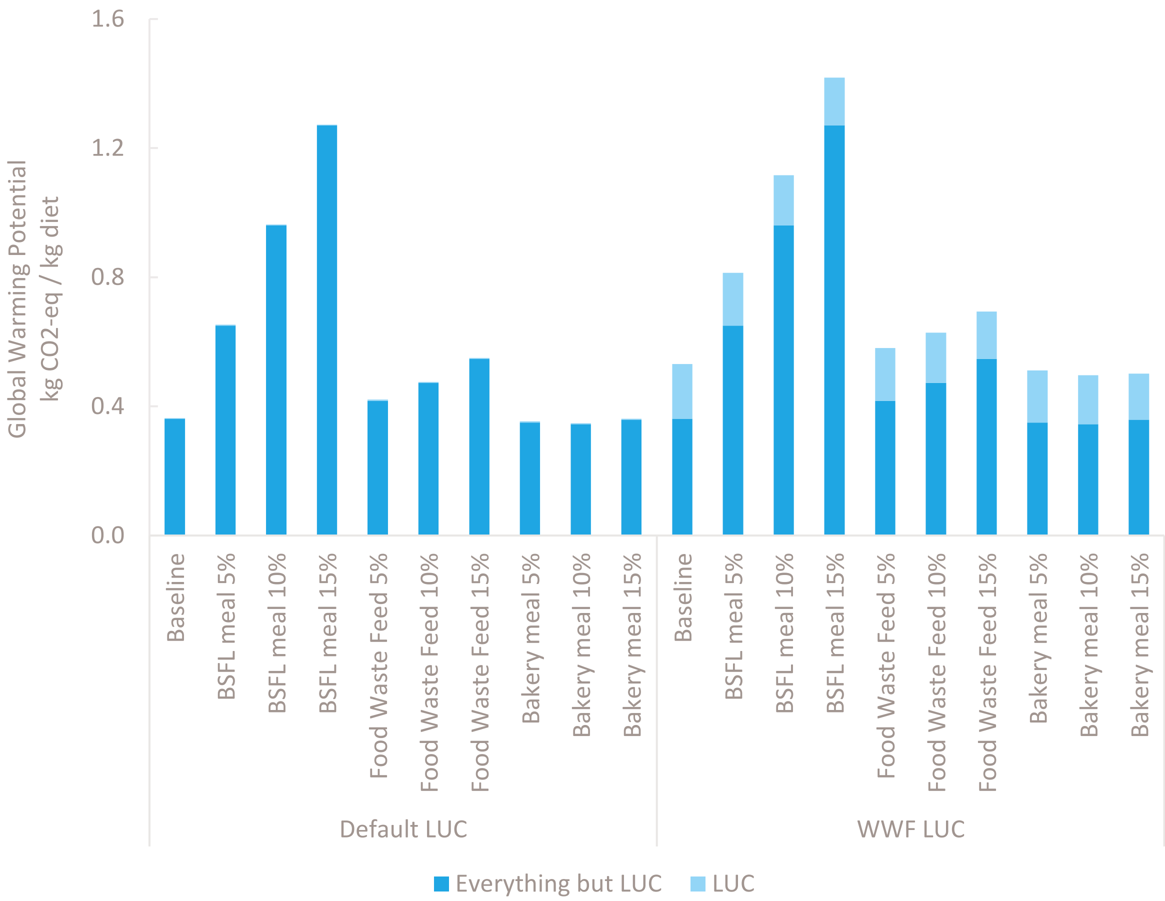

Figure 12: Impacts for the 10 diets with outlined LUC for agricultural products (corn, DDGS, soybean meal) with the University of Minnesota and University of Wisconsin method (otherwise named 'WWF LUC'). Impacts are shown next to the default WFLDB scores.

The overall trend among diets is kept constant regardless the LUC method choice and, hence, the overall conclusions are not changed. Despite this, when applying the alternative LUC approach, a 20-50% increase in GHG emissions per kg of diet is noticed when compared to the baseline method. It shall be kept in mind that overall LUC is not a key parameter to drive the GWP impact of the examined diets, and changes in GHG emissions are consistent disregarding the methodology used.

Table 11: Impacts for the 10 diets with outlined LUC GHG emissions for the default and the WWF method. LUC refers only to the agricultural ingredients of the diet, namely corn, soybean meal, and DDGS.

GHG emissions (kg CO_2-eq./kg diet)			
Diets	Everything but LUC	Default LUC	WWF LUC
Baseline	0.362	0.002	0.169
BSFL meal 5%	0.651	0.003	0.163
BSFL meal 10%	0.961	0.002	0.155
BSFL meal 15%	1.271	0.002	0.148
Food waste feed 5%	0.418	0.003	0.163
Food waste feed 10%	0.473	0.003	0.155
Food waste feed 15%	0.547	0.002	0.146
Bakery meal 5%	0.350	0.003	0.162
Bakery meal 10%	0.345	0.003	0.152
Bakery meal 15%	0.358	0.003	0.143

5.3. Sensitivity analysis

Sensitivity analyses are conducted to test the effect of key parameters to the environmental profiles of the diets. The global warming potential indicator is chosen as the most interesting and representative perspective to discuss the sensitivity of the system, and if the trend in the other indicators varies those are discussed as well.

5.3.1. Using food instead of food waste for alternative ingredients production

Using food instead of food waste would lead to no benefits in any diet. Changing the cut-off criterion for the production impacts of grocery and bakery products, increases the GHG emissions of the per-kg production of the food replacements, and subsequently the overall impacts of alternative diets. The increase in the alternative diets is at 15-85% for the different levels of alternative ingredients inclusion, rendering them all more intensive in GHG emissions.

An increase is noticed among all other indicators (Table 12). Food waste feed diets show a higher increase compared to the ither diets with equivalent food waste ingredient content. Bakery meal diets show a lower sensitivity to this parameter, due to a lower input of the bakery product compared to the grocery-based (fresh weight) input for the food-waste-based ingredient manufacturing.

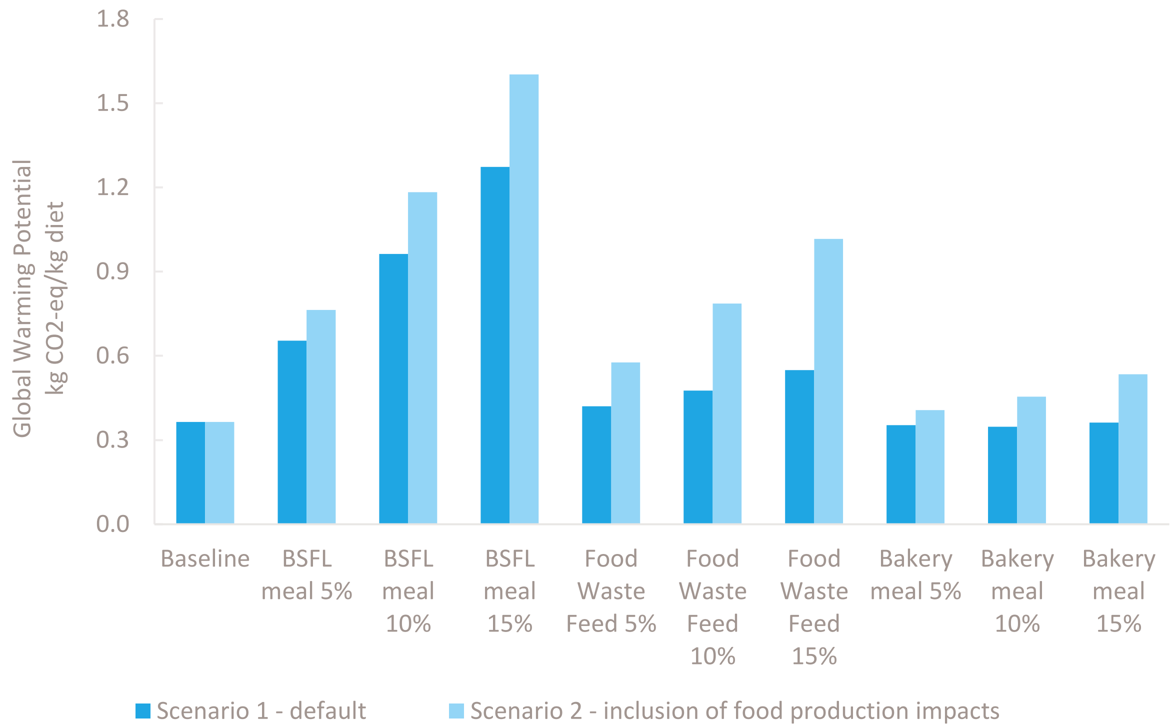

Figure 13: Sensitivity analysis for food instead of food waste in hens' diets

Table 12: Relative increase of impact to the default scenario (cut-off criteria for grocery and bakery food waste). The relative (%) increase of Scenario 2 is shown for all diets and indicators. No change for the baseline diet as it includes no food waste ingredients.

Diets	Global warming potential	Land use	Water consumption	Marine eutrophication
Baseline	0%	0%	0%	0%
BSFL meal 5%	17%	17%	996%	32%
BSFL meal 10%	23%	41%	1754%	62%
BSFL meal 15%	26%	67%	2344%	92%
Food waste feed 5%	37%	23%	1497%	47%
Food waste feed 10%	65%	53%	2940%	100%
Food waste feed 15%	85%	93%	4113%	155%
Bakery meal 5%	15%	9%	19%	18%
Bakery meal 10%	31%	17%	39%	38%
Bakery meal 15%	48%	27%	62%	61%

5.3.2. Food-waste processing electricity

Electricity consumption during processing is a hotspot for the BSFL meal and food waste feed. This sensitivity analysis shows that when using electricity from renewable solar power, we can achieve a reduction of 4.3 kg CO_2-eq / kg ingredient or 64% GWP reduction for the BSFL meal, 0.7 kg CO_2-eq / kg ingredient or a 35% impact reduction for the food waste feed, and a reduction of less than 0.1% for the bakery meal.

At a diet level. this translates to an overall benefit up to -51% in GWP (Figure 14). Larger benefits are noticed for the BSFL diets (33-51% reduction), as electricity is one of the key inputs during manufacturing. The bakery meal diets show lower sensitivity to that parameter, as electricity input is not as significant during processing as for the BSFL (and food waste feed) ingredients. Nevertheless, even using renewable electricity during BSFL meal and food waste feed production, diets using these ingredients would still lead to higher GHG emissions.

Regarding the other environmental indicators, the incorporation of renewable electricity offers benefits for the Water consumption and Eutrophication aspects, and a potential for an impact increase for the Land use indicator, with the BSFL diets showing the largest sensitivity to this parameter among the three types of diets. Benefits range between 0.1-21% reduction for water consumption, with increased benefits proportional to increased percentage of alternative food-waste-based ingredients, with higher benefits noticed for the BSFL diets. Minimal changes, lower than 0.01%, are obtained for eutrophication.

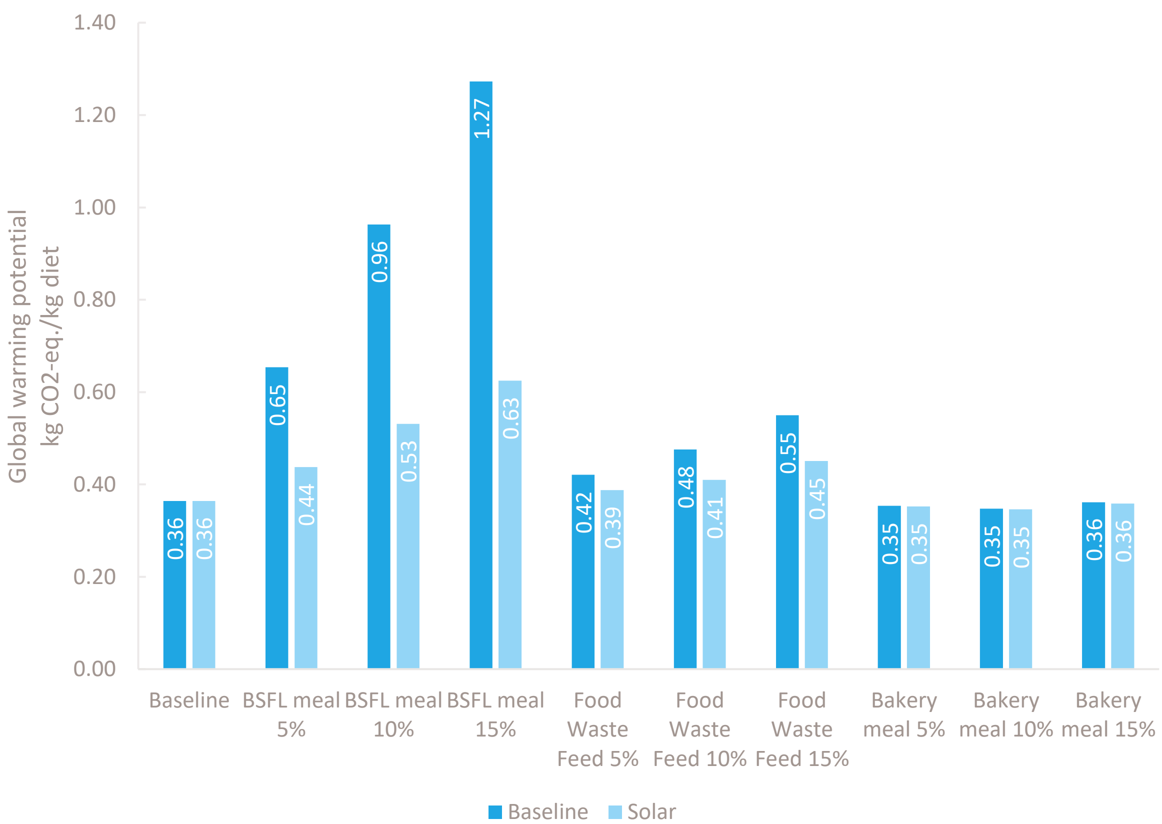

Figure 14: Sensitivity analysis for replacement of average country-mix electricity with electricity from solar power for the three food-waste-based ingredients.

5.3.3. Bakery meal production method

Suppliers provided us with three production routes for the bakery meal.The bakery meal from Supplier 2-A may lead to a doubling of the per-kg carbon footprint mainly due to higher heating needs and needs to process packaging of bakery waste which are incinerated. In contrary, the Supplier 2-B meal has a 40% lower carbon footprint, as it is manufactured through a simpler and less input-intensive process compared to the default meal. The overall diet's GWP impact would increase from 3% to 8% by including 5-15% of the meal from Supplier's 2-A bakery. On the opposite side, the overall reduction when using the bakery meal from Supplier 2-B would be from 1% at a 5% inclusion to 4% at a 15% inclusion.

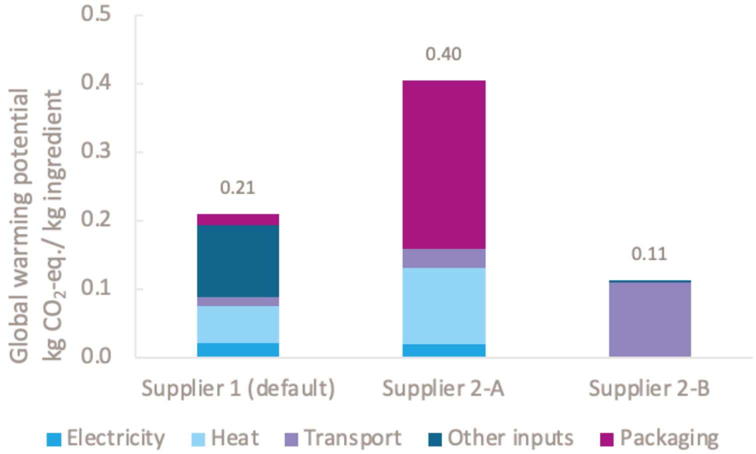

Figure 15: Comparison and contribution analysis for default and supplementary bakery meals

5.4. LCA limitations

This LCA performed for the WWF compares the production of laying hens' nutrition diets that use different agents of processed food waste feed against a conventional baseline diet. Any conclusion described by this report must be considered only within the context of the study and with considerations of the assumptions made and study limitations.

Results of this exercise can be used to accomplish the following:

- Characterize the environmental profile of the 10 laying hens' diets in the US, as well as its "hot spots" and key parameters driving these results;
- Identify potential environmental savings that the alternative diets may have as opposed to the baseline nutrition of laying hens in the US.

There are limitations in the current study that should be reiterated and that might be made the focus of future work. The study's assumptions and limitations are as enlisted below:

- Potential GHG emissions from microbial respiration during BSFL meal production are not included in this LCA and may increase the total GHG score (Parodi, 2020).
- L-Lysine is modeled with proxy data as enzyme due to lack of more accurate data on this amino-acid in Ecoinvent. The score of this ingredient may change if a more accurate models is available.

- Several ingredients in the diets are modeled with general datasets for organic or inorganic chemicals due to lack of more precise datasets. Those ingredients represent up to 2% of the total diet and more accurate models would potentially affect their environmental score.
- The use of dataset for "Animal/vegetable fat" is used based on assumptions and available datasets in Ecoinvent and the WFLDB on beef and canola oil fats. As this is one of the key ingredients in diets, more accurate data shall improve the preciseness of the outcomes of the study.
- This study is a cradle-to-gate assessment, and potential benefits of avoiding the treatment of food waste are not covered. Hence, further research should be done to assess if the benefits of avoiding the treatment of food waste, by landfill or other commonly used methods, could outweigh the potential increase in GHG emissions or water consumption.
- This study results are constrained to the US, were crops have high yields and relative low LUC related GHG emissions. Results could change for countries where crops have lower yields or higher associated LUC emissions.
- This study is looking at one impact assessment method and interpretation of the results highly depends on this method choice. With the inclusion of additional impact assessment methods and characterization factors, we can have a more complete view of the outcomes of the study.

6. Conclusions

This study is an assessment of US laying hens' nutrition with incorporated feed derived from processed produce or bakery food-waste. The goal of the study is to identify to which degree the replacement of conventional feed ingredients with alternative ones made from food waste allows for environmental benefits for hens' diet production. This is done by examining three alternative ingredients and their inclusions on hen's diets at three different levels.

Results show that no diet led to clear environmental benefits in all the environmental impacts assessed under this study, but rather to environmental trade-offs. Results highly depend on the environmental profile of the food-waste-based ingredient together with the exact composition of each diet.

Regarding global warming potential, none of the diets including food-waste ingredient show to lead to meaningful reduction in GHG emissions, with "bakery meal – 10%" leading to the largest reduction of 5% and the "BSFL meal – 15%" diet showing the largest increase of 350% when compared against the baseline. BSFL meal and food waste feed diets have a higher carbon footprint compared to the baseline, as their carbon footprint is larger than ingredients being replaced, including soybean meal and animal/vegetable fat, mainly driven by high energy demand during production.

All alternative diets have the potential to reduce land use in comparison to the baseline. The increased food replacement content facilitates the decrease in this impact, due to a reduction of agriculturally sourced feed ingredients such as soybean meal and animal/vegetable fat by food-waste-based ingredients. Between 0.06 and 0.45 m2a (4%-51%) of occupied land can be saved annually with the incorporation of food-waste ingredients.

Regarding water consumption, only bakery meal diets lead to moderate savings of around 3% when compared to baseline diet, as opposed to all other diets which lead to higher impact when compared against the baseline diet. All alternative diets can lead to lower marine eutrophication potential (2% - 15% lower) when compared to the baseline diet, but the "BSFL Meal – 15%", which leads to a 2% increase. Replacing agricultural products such as corn, soybean meal, and animal/vegetable fat leads to decreased nitrogen emissions from fertilizer use, a reduction which is larger than nitrogen emissions occurring during the production of food waste based ingredients.

For diets of the same type, increasing the food-waste ingredient in the diet aligns with a decrease in LUC and respective GHG emissions. This study shows that we reduce LUC when using the alternative diets, and even contribute to higher savings with incorporating food-waste ingredients at higher rates. At GHG impact level, all alternative diets allow savings from LUC. When applying the WWF LUC approach next to your default WFLDB method, a 20-50% increase in noticed in the overall per-kg diet impact across all diets (including the baseline). The overall trend among diets is kept constant regardless the LUC method choice and, hence, the overall conclusions are not changed.

Using food instead of food waste would lead to no benefits in any diet. Changing the cut-off criterion for the production impacts of grocery and bakery products, increases the GHG emissions of the per-kg production of the food replacements, and subsequently the overall carbon footprint of alternative diets at 14-85%. All other indicators are also increased. This sensitivity analysis highlights the importance and potential benefits of the application of waste as feed input in hens' nutrition.

When using electricity from renewable solar power, we achieve a GWP impact reduction for the three alternative ingredients per-kg of ingredient. Although benefits can be significant at a diet level, e.g., a 51% reduction for the diet with 15% of BSFL meal, emissions are still higher than the baseline for diets incorporating BSFL meal and food waste feed. Regarding the other environmental indicators, the incorporation of renewable electricity offers benefits for the Water consumption and Eutrophication aspects, and a potential for impact increase for the Land use indicator. Across indicators, the BSFL diets show the largest sensitivity to this parameter compared to the other sets of diets. Prioritizing renewable electricity or manufacturing these ingredients in regions where electricity has a low carbon footprint, can provide for significant environmental benefits for diets using BSFL meal and food waste feed.

In conclusion, this study has shown that including food-waste-based ingredients in hen layers' diets can lead to environmental trade-off, mostly to increases in the carbon footprint and potential water consumption, but providing benefits on land use, land use change, and marine eutrophication. These findings indicate that the use of food waste as feed for laying hens has the potential for only modest environmental improvement, while carrying risks of significantly higher environmental impact. As a significant amount of the impact of the food waste alternatives is related to energy use, the outcomes of food waste as a feed ingredient can be improved significantly using renewable energy. Given the interest in establishing routes such as poultry feed as a positive end use of wasted human food products, the finding here that the benefits are small, or even non-existent, suggests that emphasis should be kept on preventing food waste wherever possible as a top priority. The report findings also suggest that new uses of food waste should be assessed in a case-by-case scenario to avoid unexpected environmental consequences, such as the increase in GHG emissions on animal diets. If pursuing food waste as a feed based on the current technologies here, use of renewable energy and other efforts to minimize environmental impact are needed to consider this a positive environmental outcome.

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7. Appendices

7.1. Appendix I – Description of impact categories

Global warming potential

Model: Bern model – Global Warming potentials (GWP) over a 100-year time horizon (IPCC 2013)

Unit: kg CO_2-eq.

Impact category that accounts for radiative forcing caused by greenhouse gas (GHG) emissions such as carbon dioxide (CO_2), methane (CH_4) or nitrous oxide (N_2O). The capacity of a greenhouse gas to influence radiative forcing is expressed in terms of a reference substance (carbon dioxide equivalents) and considers a time horizon of 100 years following the guidelines from the Intergovernmental Panel on Climate Change (IPCC 2013). Radiative forcing is the mechanism responsible for global warming.

Land use

Model: Soil quality index based on LANCA model (Beck, Bos, Wittstock, Baitz, & Sedlbauer, 2010; Bos, Horn, Beck, Lindner, & Fischer, 2016)

Unit: points (Pt, dimensionless)

The LANCA® (Land Use Indicator Value Calculation in Life Cycle Assessment) model assesses the environmental impact from land occupation and land transformation through four indicators: biotic production, erosion resistance, mechanical filtration, and groundwater replenishment. The European Commission Joint Research Centre (JRC) aggregated these into a single Soil Quality Index. The LANCA®

Water consumption

Model: AWARE 100 (Boulay, Bare, & Benini, 2017)

Unit: m^3 water deprived-eq

This impact indicator assesses the potential of water deprivation, to either humans or ecosystems, building on the assumption that the less water remaining available per area, the more likely another user will be deprived. It is based on the AWARE 100 model, the recommended method from WULCA for water consumption impact assessment in LCA.

Marine eutrophication

Model: EUTREND model (Struijs et al. 2009)

Unit: kg N-eq.

Impact category that addresses impacts from nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilized farmland which accelerate the growth of algae and other vegetation in marine water. The degradation of organic material consumes oxygen resulting in oxygen deficiency. In marine environments, nitrate (NO_3) is considered the limiting factor. The impact metric is expressed in kg N-eq (kg nitrogen to water equivalents).

Resource use, energy carriers

Model: CML 2002 model (Guinée et al., 2002; van Oers et al. 2002 ; (Fazio, Biganzioli, & Laurentis, 2018)

Unit: MJ

Category that measures the potential impact on non-renewable resource depletion from energy carriers (i.e., fossil fuels and uranium). The impact metric is expressed in MJ (megajoules).

7.2. Appendix II – Inventories of Waste-to-Feed ingredients

The inventories for the LCA of the Waste-To-Feed ingredients are registered in the Excel file "*WWF_Quantis_FoodWastetoFeed_Inventories_Appendix_20200914.xlsx*"

This document is a confidential document, intended for the review process.

7.3. Appendix III - Review panel

Name	Short name	Organization
Paul Patterson	PP	Penn State
Hannah van Zanten	HZ	University of Wageningen, Netherlands
Ned Spang	NS	UC Davis
Nathan Pelletier	NP	University of British Columbia, Canada
Shannon Kenny	SK	EPA
Greg Downing	GD	Cargill
Marty Matlock	MM	University of Arkansas
Helen Anne Hudson	HH	Burnbrea Farms, Canada
Lisa Zwack	LZ	Kroger Company
Justin Ransom	JR	Tyson Foods
Ezra Kahn	EK	USDA
Karel van der Velden	KV	Granico
Andreas Lemme	AL	Evonik
Justin Kamine	JK	KDC Ag
Advisory Group	AG	Comment: Feedback received from Advisory Group call on the 17th August 2020

7.4. Appendix IV – Nitrogen-containing substances with Nitrogen Assessment characterization factors

Nitrogen-containing substance
Ammonia
Ammonium nitrate
Ammonium, ion
Dinitrogen monoxide
Hydrazine
Nitrate
Nitric acid
Nitrogen
Nitrogen dioxide
Nitrogen monoxide
Nitrogen oxides
Atmospheric nitrogen
Nitroglycerine
Nitrous acid
2,4,6-trinitro-toluene

7.5. Appendix V – LCIA scores for the baseline and the alternative diets for all indicators (main and supplementary)

Diets	Global warming potential ($kg\ CO_2$-eq./kg diet)	Land use (Pt/kg diet)	Water consumption (L/kg diet)	Marine eutrophication (g N-eq./kg diet)	Nitrogen assessment (g Nr-eq./kg diet)	Resource use, energy carriers (MJ/kg diet)
Baseline	0.36	174.43	4.50	2.94	4.06	3.58
BSFL meal 5%	0.65	149.78	4.88	2.90	3.91	8.68
BSFL meal 10%	0.96	127.28	5.54	2.95	3.89	14.08
BSFL meal 15%	1.27	115.15	6.22	2.99	3.84	19.40
Food waste feed 5%	0.42	156.40	4.60	2.78	3.75	4.92
Food waste feed 10%	0.48	137.66	4.68	2.58	3.41	6.24
Food waste feed 15%	0.55	117.87	5.02	2.52	3.24	7.85
Bakery meal 5%	0.35	167.07	4.37	2.83	3.89	3.50
Bakery meal 10%	0.35	160.37	4.31	2.74	3.75	3.49
Bakery meal 15%	0.36	161.23	4.38	2.65	3.57	3.87

7.6. Appendix VI – LCIA results for Land Use Change and LCI for Land transformation and Land occupation per kg diet

Diets	Land Use Change (impact)	Land Use Change (inventory)	Land occupation
	(kg CO_2-eq./kg diet)	(m2/kg diet)	(m2a/kg diet)
Baseline	9.977	0.762	1.334
BSFL meal 5%	7.680	0.720	1.147
BSFL meal 10%	5.404	0.705	0.976
BSFL meal 15%	2.977	0.687	0.885
Food waste feed 5%	7.356	0.718	1.195
Food waste feed10%	4.520	0.669	1.051
Food waste feed15%	2.235	0.653	0.898
Bakery meal 5%	10.471	0.726	1.278
Bakery meal 10%	10.975	0.695	1.227
Bakery meal 15%	10.748	0.664	1.234

7.7. Appendix VII – LCIA scores for baseline and alternative diets where production impacts for alternative feed are included (no cut-off for food waste)

Diets	Global warming potential	Land use	Water consumption	Marine eutrophication
	(kg CO_2-eq./kg diet)	(Pt/kg diet)	(L/kg diet)	(g N-eq./kg diet)
Baseline	0.36	174.43	4.50	2.94
BSFL meal 5%	0.76	175.61	53.45	3.81
BSFL meal 10%	1.18	178.95	102.69	4.78
BSFL meal 15%	1.60	192.65	151.94	5.74
Food waste feed 5%	0.58	193.00	73.41	4.07
Food waste feed 10%	0.79	210.85	142.30	5.18
Food waste feed 15%	1.02	227.66	211.45	6.41
Bakery meal 5%	0.41	181.30	5.19	3.35
Bakery meal 10%	0.45	188.23	5.97	3.77
Bakery meal 15%	0.53	204.03	7.07	4.25

7.8. Appendix VIII – LCIA scores for baseline and alternative diets with solar power for processing alternative feed ingredients

Diets	Global warming potential (kg CO_2-eq./kg diet)	% difference to default scenario	Land use (Pt/kg diet)	% diff. to default scenario	Water consumption (L/kg diet)	% diff. to default scenario	Marine eutrophication (g N-eq./kg diet)	% diff. to default scenario
Baseline	0.36	0%	174.43	0.00%	4.50	0.00%	2.94	0.00%
BSFL meal 5%	0.44	-33%	151.59	1.21%	4.44	-8.88%	2.90	0.00%
BSFL meal 10%	0.53	-45%	130.89	2.84%	4.67	-15.62%	2.95	-0.01%
BSFL meal 15%	0.63	-51%	120.57	4.71%	4.92	-20.89%	2.99	-0.01%
Food waste feed 5%	0.39	-8%	156.68	0.18%	4.53	-1.44%	2.78	0.00%
Food waste feed 10%	0.41	-14%	138.21	0.40%	4.55	-2.82%	2.58	0.00%
Food waste feed 15%	0.45	-18%	118.70	0.70%	4.82	-3.95%	2.52	0.00%
Bakery meal 5%	0.35	0%	167.08	0.00%	4.37	-0.04%	2.83	0.00%
Bakery meal 10%	0.35	-1%	160.39	0.01%	4.31	-0.09%	2.74	0.00%
Bakery meal 15%	0.36	-1%	161.26	0.02%	4.37	-0.13%	2.65	0.00%

7.9. Appendix IX- Nutritional profiles of poultry diets

Nutritional Profile of diets (1 kg)											
		Baseline	Bakery byproduct meal			Food waste feed			BSFL meal		
	Units		5%	10%	15%	5%	10%	15%	5%	10%	15%
Dry Matter	%	85.6	86.0	86.5	87.3	86.6	87.6	88.5	86.8	87.9	89.3
Metabolizable Energy	kcal/kg	2,833	2,833	2,833	2,833	2,833	2,833	2,833	2,833	2,833	2,833
Crude Protein	%	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5	16.5
Ether Extract	%	6.171	6.211	6.250	5.532	6.350	6.529	7.039	5.860	5.548	4.683
Linoleic Acid	%	2.175	2.054	1.932	1.577	2.077	1.978	1.979	2.131	2.087	1.840
Crude Fiber	%	2.196	2.358	2.521	2.487	2.279	2.362	2.518	2.414	2.633	2.664
Ash	%	6.315	6.377	6.438	6.407	6.538	6.664	7.105	6.393	6.281	6.484
Arginine	%	0.869	0.860	0.851	0.861	0.825	0.780	0.721	0.812	0.756	0.736
Glycine	%	0.545	0.541	0.538	0.548	0.508	0.471	0.425	0.551	0.558	0.588
Serine	%	0.679	0.673	0.667	0.668	0.636	0.593	0.544	0.654	0.631	0.625
Histidine	%	0.367	0.363	0.360	0.357	0.353	0.340	0.323	0.352	0.338	0.331
Isoleucine	%	0.575	0.570	0.564	0.563	0.552	0.529	0.500	0.563	0.552	0.557
Leucine	%	1.308	1.289	1.270	1.205	1.267	1.225	1.196	1.300	1.290	1.250
Lysine	%	0.740	0.740	0.740	0.740	0.740	0.740	0.740	0.740	0.740	0.740
Methionine	%	0.413	0.414	0.414	0.789	0.426	0.439	0.451	0.426	0.440	0.456
Cystine	%	0.227	0.226	0.227	0.219	0.214	0.201	0.189	0.214	0.200	0.184
Methionine + Cystine	%	0.640	0.640	0.640	1.009	0.640	0.640	0.640	0.640	0.640	0.640
Phenylalanine	%	0.698	0.693	0.688	0.684	0.666	0.635	0.598	0.670	0.643	0.627
Tyrosine	%	0.641	0.634	0.627	0.631	0.611	0.582	0.544	0.668	0.696	0.745
Threonine	%	0.507	0.499	0.491	0.485	0.485	0.463	0.438	0.501	0.497	0.503
Tryptophan	%	0.156	0.155	0.155	0.159	0.148	0.140	0.130	0.153	0.152	0.157
Valine	%	0.657	0.651	0.645	0.636	0.634	0.611	0.586	0.668	0.679	0.698
Calcium	%	4.200	4.200	4.200	4.200	4.200	4.200	4.200	4.200	4.200	4.200
Total Phosphorus	%	0.653	0.650	0.648	0.649	0.673	0.693	0.709	0.636	0.619	0.609
Available Phosphorus	%	0.440	0.440	0.440	0.440	0.440	0.440	0.440	0.440	0.440	0.440
Potassium	%	0.669	0.683	0.697	0.711	0.655	0.641	N/A	0.643	0.617	0.603
Chlorine	%	0.266	0.265	0.264	0.283	0.236	0.206	N/A	0.253	0.239	0.232
Sodium	%	0.170	0.170	0.170	0.179	0.170	0.170	N/A	0.170	0.170	0.170

7.10. Appendix X – Feedback from the Advisory Board on the Goal & Scope report

Comment	Response
No disclosure of food-waste ingredients inventories in the public report	Included as an independent and confidential appendix.
Clear explanation for food waste cut-off approach	Included in section 3.4.3
Include nutritional profiles of diets in the report	Included in appendix IX
Need to make sure allocation choices are consistent especially the background Ecoinvent allocation methods	Detailed allocation choices are described in the respective section on allocation
Include a Nitrogen footprint assessment instead of Eutrophication and Acidification impacts	Included
Official name is Bakery Byproduct Meal and Black Solider Fly larvae meal	Changed throughout the report
Various phrasing/terminology related corrections and missing references	Included
Revise project title	Title changed to “LCA of Waste-to-Feed diets for laying hens”
P3: Nomenclature issue. A diet is a mixture of ingredients blended to meet the nutrient specifications of a particular animal. This term should not be used below. Rather they are ingredients.	Revised for the correct use of terms “diet”, as well for “ingredient” and “feed mix”
Table 3 Issues with RENCAL - not a fishmeal, MonCal-Dical – no a sodium phosphate, Biolysine- not an enzyme	Fish meal is replaced with beef fat, MonCal - Dical is modeled as an average inorganic chemical, Biolysine is modeled as an enzyme as proxy due to lack of environmental data on aminoacids
P 6. Figure 1. This title, figure and terminology is wrong and needs help. Table 3. Diet not feed mix. Table 4. Terminology issue - chemically digested pellet.	Figure 1 is adjusted, and chemically digested pellet is renamed as food waste feed
P. 15 Figure 1 – Question – not showing any cradle to gate for corn, soybean meal etc. no transportation etc. eluded to in the paragraph? Also 3) feed mixing is the same and not necessary.	Figure 1 is adjusted with feed mixing left out of the system boundary. The production of agricultural feed products is described in the primary and secondary inventory section.
“Waste” must have a uniform, consistent nutrient content or it will be very difficult to formulate into a quality poultry feed without testing each batch for nutrient content”	This is addressed through specialized preparation of diets based on nutritional value of ingredients
“Proposed Chicken Feed composition: no animal protein source in the layer diet”	The 10 diets are prepared by collaborative WWF nutritionists
Government regulation on the use of potential feed ingredients and FDA approval are important considerations.	Waste streams are acquired through commercially available products from industrial suppliers.
Communication of the benefits of diets from waste streams would have to be through UEP/ individual egg farmer promotion in the States? In Canada we promote on egg cartons under brand names and on websites.	This is out of the scope of our study
Bakery waste is used in animal diets to the best of my knowledge. Likely only the largest bakeries though?	There are 2 large US bakery suppliers who provide information for this study
Look closely at the PEFCR Feed for food producing animals and the latest GFLI guidelines.	We looked closely at the PEFCR guidance for feed. The study is mostly aligned with the guidance, but we do not consider the feed production life cycle step (else final ingredient mixing), as it is out of the scope of

	the study and given that it is considered to be the same for the 10 alternative diets.
Advisable to show results not only in kg CO_2-eq but also show Land Use impacts. This will allow a comparison of feed made of 100% rest- or coproducts with traditional feed	This has now been incorporated in the report.
"Our company processes annually approx. 100.000 ton former foodstuff into compound feed and/or liquified and dried raw material to be used in pig feed and feed for layer hens (www.kipster.com). In the Netherland approx. 350.000 ton former foodstuff are annually used as raw material in feed. In the EU this number is approx. 3,5 up to 5 million ton annually. Therefor I think it is safe to say that it is common practice using bakery meal in feed. The general amount can differ from 3 % up to 25 % in specific pig feed though."	It is now mentioned in the report, that bakery meal use is a usual practice in animal feed nowadays
A few phrasing corrections related to the confidentiality of information that describes the KDC food waste feed fabrication	Changes have been kept.

7.11. Appendix XI – Feedback from the Advisory Board on the full report

Comment	Response
Reporting of diet scenarios appear inconsistent. I cannot figure out whether this is just due to errors in copying from Dr. Pattersons originals or not Please have particular look into treatments 15% bakery meal and 15% BSFL meal. Especially the lysine increases as reported in Appendix 3 do not make sense to me. If this is due to extra lysine supplementation which is discussed as special effect in results, a revision is needed (in case the numbers reported are not typos) è however, I do have the impression that there is also a copy paste issue between these two diets. In the same context there is an unusual reduction of fat addition in Appendix 3.	The diets table have been revised and updated in the report. The diet for bakery waste at 15% inclusion has been reformulated and all new results have been updated. All diets have been constructed by Professor Paul Patterson from Penn State to meet hen layer nutritional requirements.
While the nutrient composition of the diets is well documented in the main body and appendix, I am missing same characterization of the alternative ingredients (è nutrient profile of bakery meal, BSFL-meal, and food waste).	It has been shared privately with the review panel to respect data supplier's confidentiality
If 100% renewable energy is assumed for these products, shouldn't we have a similar assumption for the convential ingredients as well in order to have a fair comparison	This is considered out of scope.
Would it make sense to include a list of those ingredients? (ref.cut-off for materials with less 1% content)	All available data has been included, even those that represented less than 1% by mass.
Should be available – maybe not from Ecoinvent è see Kebreab et al., doi:10.2527/jas2015-9036 (ref. lysine)	Quantis uses ecoinvent and it's own internal databases that follow a methodology similar to ecoinvent. The most similar proxy from these databases is then selected to maintain consistency in methodological choices and allocation rules.
You used and defined LCA, but not LCIA here. (page 4)	Fixed
Suggest you reference Table 2 BEFORE using information from it below re. diets their percentage and impacts. This helps the reader follow your line of thought. (page 4)	Kept due to formatting considerations.
Neither is this statement clear. 1st what are the units of m2a? and why are you speaking of the merits of food waste vs. the BSFL clearly better in this category?	Fixed
Format on Append. Table and Figure titles the same. Right now some all lower case, some with some caps, not consistent.	Fixed

Add Pt and other units not defined in the tables and figures	Units either spelled out or included in the abbreviations. A complete description of the impact indicators reported can be found in Appendix I.
One note on the conclusion, there is only potential for LUC and eutrophication benefits if there is in fact a reduction in corn and soy production in direct response to integrating food waste into feed. The causal chain here seems pretty sketchy. I think something to consider in the conclusion is the environmental and economic efficiency of the current "conventional" feed systems, and comparing food waste to feed against other waste processing approaches such as landfilling, composting, incineration, etc. Maybe for future work? Perhaps this may reveal a more compelling case for the environmental benefit of pursing this technology or approach? Or perhaps it won't, just a suggestion	Thanks for the feedback. We will explore new lines of research that might address some of these questions.
Hermetia illucens in Italics	Fixed
page 19 repetitive paragraph "The system boundary of the study is aligned with the PEFCR …"	Fixed
page 20 define capital goods	Fixed
page 22 "Economic allocation is one of the widely used allocation method for multi-output agricultural systems and is considered to be addressing the main driver for these production systems- revenue and demand" -- awkward sentense	Rephrased
page 32 "BSFL meal and food waste feed diets show consistent higher global warming and water consumption potential though lower land use and marine eutrophication potential, as in both cases the inclusion of alternative ingredients lead to replacing ingredients with lower global warming or water consumption potential, like soybean meal and animal/vegetable fat." -- awkward sentence	Rephrased
page 39 "Moreover, the WFLDB method reports annualized average emissions over a 20-year period, as opposed to the UNM approach which accounts for the total emitted carbon over the considered time span, being it a factor that allows to explain the higher scores results by the latter method. "	Rephrased
page 40 "Moreover, when applying the alternative LUC approach, a 20-50% increase is noticed in the overall per-kg diet GHG emissions across all diets, when comparing with the respective diet with default GHG LUC emissions." -- awkward sentence	Rephrased

I'm not sure this analysis is particularly useful. By definition the environmental impacts will increase if we define the inputs as food instead of food waste. And I can't a imagine a situation where we would divert high quality food intended for human consumption (that is not food waste) to animal feed. (ref no cut-off)	This scenario was included to study the effects of allocation choices under a worse-case scenario per the science advisory panel request
Figure 14 does not seem to be showing a ~10% reduction in GWP for bakery meal with the use of renewables…	Reduction was less than 0.1%. Language changed in the report.
The numbers listed in this sentence are for what percentage of incorporation of each FW ingredient? (page 43)	Language changed
What do you mean an overall benefit? Across the feed types? Can this value be additive? And compared to what – the baseline? (page 43)	Language changed
Above you mention a 64% reduction in GWP with renewables for BSFL – which is correct? (page 43)	Different percentages are for the ingredient level or diet level. Language changed and clarified
"Prioritizing renewable electricity can provide for significant environmental benefits for all diets, with special attention for the BSFL meal and food waste feed formulations." -- The results actually do not support this statement. Renewable electricity has minimal impact on both the baseline and the bakery meal diets. (page 45)	Language changed
(page 46 closing paragraph) It is already well-known already that FLW prevention is better than waste management. And, this study provides no assessment of prevention approaches. So, I find this conclusion to be rather vague/generic. I suggest making a more specific statement here about the need for granular assessment of potential treatment pathways to ensure that proposed solutions are indeed as environmentally friendly as they are presumed to be. Avoiding potential negative environmental benefits from novel FLW approaches will require rigorous assessment in the design phase, as well as evidence-based evaluation in their deployment. // Awkward sentence, and again, not a particularly accurate conclusion relative to the bakery meal pathway.	Language changed

I would argue as well that the role of livestock should be limited to the amount of leftovers available (Van Zanten et al., 2018). Yes, I agree that we should always reduce food waste and consume it ourselves (we also stress this in van Zanten et al., 2019). But the fact that the benefits in your results are limited is also because you only include a small amount of waste products in the feeds. If you would only feed waste products to livestock the environmental impact is reduced a lot (see Van Selm et al., 2021 or Van Hal et al., 2019 Kipster paper). Yes, I realize that only feeding leftovers is not realistic but your conclusion that feeding waste is not so beneficial is in my opinion not correct or should at least contain more nuances. (page 44 limitations)	Results in this study shows that due to high energy consumption during production of food-waste based ingredients diets using this ingredients can have to higher GHG emissions, with increasing emissions at higher level of inclusions. Future research is recommended to account for potential benefits of avoiding landfill or other commonly used waste management methods. Also, results are constrained to the US, were crops have high yields and relative low LUC related GHG emissions - These results could change for countries where crops have lower yields or higher associated LUC emissions.
(page 46 closing paragraph) It is already well-known already that FLW prevention is better than waste management. And, this study provides no assessment of prevention approaches. So, I find this conclusion to be rather vague/generic. I suggest making a more specific statement here about the need for granular assessment of potential treatment pathways to ensure that proposed solutions are indeed as environmentally friendly as they are presumed to be. Avoiding potential negative environmental benefits from novel FLW approaches will require rigorous assessment in the design phase, as well as evidence-based evaluation in their deployment. // Awkward sentence, and again, not a particularly accurate conclusion relative to the bakery meal pathway.	Language changed
Maybe a note here that the transferability of the results should take into account the electricity grid mixes of different countries. Based on this finding, the waste to feed pathways in Canada may be more interesting given the much greener electricity grid mixes in most Canadian provinces!	Language added
in the United States at present (page 5 In summary, these findings indicate that the use of food waste as feed for laying hens)	Added "in the US"
(page 12) Moreover, food waste recycling with nutrient and energy recovery after processing of by-products or food waste results in significant domestic savings -- What do you mean? Savings for households? How? (money?)	Monetary savings. Changed.
Why these options, specifically? (ref bakery meal etc)	Selected due to access to data
Why this geography? (ohio Iowa Penn)	Selected due to WWF interests

Page 19) "This study assesses the life cycle of feed for egg production, from the extraction and processing of all feed ingredients " add "excluding feed milling"	Done
You need to define and better justify use of the cut-off approach. It is a non-obvious choice, and very important to understanding the quantified burdens. I believe that a rationale was articulated in collaboration with the Advisory Committee, based on the desire to focus this study on developing robust inventories for the actual feed-waste-to-feed production technologies, specifically (page 21)	This was discussed and agreed with the Advisory Committee at the beginning of the study.
So… how does this correspond to the ISO 14044 allocation hierarchy? (ref ecoinvent cut-off by classification page 22)	This was discussed and agreed with the Advisory Committee at the beginning of the study.
Why would you include this? It's short cycling carbon, not a net contribution to GHG emissions… (ref "we shall note that CO2 emissions from microbial respiration may have a substantial contribution (up to 34%) to the overall Global warming potential of the meal, and, as this aspect is not covered in the present assessment, it is listed as a limitation of the study (Parodi, 2020)" page 31)	Language removed
Unclear why this is considered a relevant sensitivity analysis. A sensitivity analysis of allocation decisions would be more relevant and provide similar results. (ref no cut-off)	This was discussed as a worst-case scenario at the beginning of the project with the Advisory Committee.