BIODIVERSITY IMPACT ASSESSMENT OF DIFFERENT MEAL OPTIONS BASED ON LIFE CYCLE ASSESSMENT (LCA)

Comparison of vegan, vegetarian and meat-based meal options

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Biodiversity impact assessment of different meal options based on life cycle assessment (LCA)

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Biodiversity loss due to food production activities is a major global challenge that needs to be addressed immediately. Pollution, greenhouse gas emissions, water consumption, deforestation and other impact pathways resulted due to the agricultural activities and the food supply chain contributes to major biodiversity losses. Dietary practices of the individuals and consumption patterns can influence the food production system. More often the consumers are unaware of the impacts caused due to their food consumption. The aim of this thesis was to assess the biodiversity impacts and environmental impacts resulting from the life cycle of six different meals from different category of meals, i.e., meat based, vegetarian, vegan and plant-based meat alternative meal options. The impacts were assessed from cradle to plate, and the results are used to support the decision making for the food service provider and consumers. Life Cycle Assessment (LCA) was used to assess biodiversity impacts using LC-IMPACT method, and environmental impacts of the meals were assessed using ReCiPe 2016 method. Results indicated that on an average, meal containing animal-based products had higher biodiversity impacts and environmental impacts when compared to the meals comprising of plant-based ingredients. Significant reductions in the overall impacts were achieved by replacing animal-based ingredients (e.g., beef) with plant-based ingredients (e.g., tofu). The outcome of the study proposes that gradually transitioning from animal-based meals from plant-based diets can reduce the biodiversity impacts from food production system, and support to safeguard the biodiversity.

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SYMBOLS AND ABBREVIATIONS

Abbreviations

ADEME	French Environment and Energy Management Agency
AE	Aquatic Ecosystem
BAHY	Biodiversity Adjusted Hectare Year
BF	Beef Lasagne
CF	Characterization Factor
EBV	Essential Biodiversity Variables
ECV	Essential Climate Variables
EU	European Union
FAO	Food and Agriculture Organization
FEP	Freshwater Eutrophication Potential
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LBC	Lemon Broiler Chicken
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LOP	Agricultural Land Occupation Potential
LUKE	Natural Resources Institute Finland
LULUC	Land Use and Land Use Change

MS	Microsoft
PDF	Potentially Disappeared Fraction of Species
PSP	Pea Soup with Pork
PST	Pea Soup with Tofu
SC	Spinach Crepes
TE	Terrestrial Ecosystem
VC	Vegan Casserole
WCP	Water Consumption Potential
WFLDB	World Food LCA Database
WWF	World Wildlife Fund

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1 Introduction

1.1 Background

The abundance in biodiversity is indispensable for the efficient functioning of the ecosystem and its characteristics. Biodiversity is elemental due to its contribution towards various resources and benefits to human civilization. (Gamfeldt et al., 2008) However, the global biodiversity is diminishing at an alarming rate, and the primary catalyst for this decline is the human activities and its impact on ecosystems (Lazarus et al., 2015). The depletion of biodiversity is considered as one of the major concerns when evaluating the impacts on the environment. Biodiversity refers to the diverse array of living organisms found on Earth, encompassing various biological constituents such as species composition, structure, function, genetic diversity and organization, connectivity and fragmentation, as well as population and community. (Turner et al., 2019) As per the estimates from World Wildlife Fund (WWF), by 2020 the planet has experienced a loss of over two-thirds of its wildlife population in a time span of just 50 years (Brachet et al., 2019).

Biodiversity is diminishing due to a confluence of factors such as habitat destruction, invasion by non-native species, excessive harvesting, nutrient accumulation, and release of toxic substances to the environment, in addition to the growing and emerging impacts of climate change. This loss of biological species across the globe is irreversible and may have larger implications on the survival of other species and on the overall functioning of the ecosystem. (Callesen, 2016) Consequently, it can result in the disappearance of the diverse life forms present on the earth and deprivation of the services affiliated with that. The biodiversity services are categorised into 4 groups: “supporting services (nutrient cycles, soil formation, etc.), provisioning services (food, fresh water, fuel, materials, etc.), regulating services (climate, flood and disease regulation, water depollution, etc.) and cultural services (well-being, aestheticism, hobbies, etc.)”, unavailability of these services can be detrimental for the human society. (Brachet, Schiopu and Clergeau, 2019) In addition, the resilience of an ecosystem is higher with the higher biodiversity to counter the effects of the climate change (Winter *et al.*, 2017).

The main drivers triggering in the terrestrial biodiversity loss are land use and land use change (LULUC), climate change, invasive non-native species, pollution, and overutilization of the natural resources. Among which, land use and land use change had the most significant impact during the past decades. (Souza, Teixeira and Ostermann, 2015) Land use and land use change due to agricultural practices is a significant contributor to the decline in the global biodiversity currently as well as in the anticipated future (de Baan *et al.*, 2015). This can be attributed to the consequence of growing demand for food and energy, driven by the rising global population. Sustaining food security for the future, while suspending the biodiversity loss has become a difficult task. (Mueller, de Baan and Koellner, 2014) Several developing countries have converted their land that are abundant in biodiversity, into cash-crop producing fields for the developed countries. It is estimated that 30% of the threat to the global species is from the result of international trading of agricultural, fishery, forestry products. More often, customers and the policy makers are uninformed about the repercussion of such imported products. (de Baan *et al.*, 2015) More than 6000 plant species are grown for the purpose of food globally, among them only nine species accounts for around 66% of the overall food production (Moreau and Speight, 2019).

The current global food system is driven by the increased productivity, while maintaining lower food prices which assures the food security by strengthening the access to food. However, the costs of the impact on the natural ecosystems and human health from this food production system is still imprudent. The increased yields as the result of intensification of the agricultural practices with the amalgamation of fields, use of pesticides, herbicides, fertilizers, equipment, and other processes have been detrimental to the biodiversity, as it deteriorates the food sources, water and habitats. The global food system is also a significant contributor towards greenhouse gas (GHG) emissions, as a result it drives the biodiversity loss indirectly by advancing climate change. (Benton et al., 2021)

Furthermore, 70-85% of the global water footprint and 30% of the global greenhouse gas emissions are the result of agricultural activities (Smetana *et al.*, 2015). Recent studies have reported that around 57% of the overall food related global GHG emissions are resulted only from the animal-based food production, while 29% is from plant-based food products and the remaining 14% is due to other purposes. Livestock grazing and animal feed production accounts for almost 80% of the agricultural land, and the remaining is used to produce food crops for human consumption. In addition, it also requires significant amounts of freshwater consumption. Though, only 18% of global calorie supply and 37% of total protein supply are contributed by meat and dairy products. (Takacs *et al.*, 2022) Several studies have been conducted where the results have clearly depicted that the meat and dairy based food versions have substantially higher environmental impacts compared to the plant-based food versions in terms of Global Warming Potential, Terrestrial Acidification, Freshwater use and depletion, and Land use. However, in some studies there is no clear distinguishing between vegetarian and vegan food versions. (Crenna, Sinkko and Sala, 2019; Takacs *et al.*, 2022)

Recently organic farming has been promoted instead of conventional farming practices, and it has been found that the organic farming practices have yielded in the increase in the amounts of the species. The management principles of the organic farming can be correlated with the benefits of having lesser negative impact on biodiversity and preserving it. (Mueller, de Baan and Koellner, 2014) In addition, further understanding of the effects on biodiversity from the different products and services available in the global market is necessary (Michelsen, McDevitt and Coelho, 2014).

Biodiversity is a complex concept, and its measurement is challenging using the commonly available direct measurement techniques, which are not able to provide the complete narrative. Life cycle assessment (LCA) is one of the prime methods that can be used to assess the biodiversity loss throughout the life cycle of the products and services, taking into consideration of the cradle-to-grave phases. LCA comprises of interdisciplinary, inclusive, comprehensive, and replicable biodiversity metrics which satisfies the necessary criteria for adequate biodiversity loss assessment. Influence of the products and services over all its life cycle stages on the biodiversity can be analysed utilising the distinct impact pathways within the LCA framework. (Souza, Teixeira and Ostermann, 2015)

In the context of Finland, due to its geolocation and climatic conditions majority of the agricultural products consumed are from foreign lands. In recent decades more than 93% of the negative impacts on the biodiversity due to imports for Finnish food supply has been accounted outside the borders of Finland. (Sandström *et al.*, 2017) It was estimated that, in the year 2010 approximately 10% of the species were endangered in Finland. Endangered status is attributed to over 95% of rural biotopes. The prime driver for this development in the rural region is the intensification of agriculture, which has endangered the species population due to habitat loss and fragmentation. (Uusitalo *et al.*, 2019) Currently, the leading form of production in Finnish agricultural sector is from the dairy and beef farming.

As a result, grass production has become significant and accounts for majority of the production along with few cereal and dicot crops. The utilisation of harmful constituents such as pesticides, herbicides, fungicides, etc., on grasslands has lesser impact on biodiversity compared to the cultivated fields. However, the short crop rotation time and intensive production might result in negative impact on the taxonomic and functional biodiversity. (Tiainen *et al.*, 2020)

1.2 Objectives

The objective of this thesis is to compare the biodiversity impacts arising from the different meal options (i.e., vegan, vegetarian or meat-based version) provided at the restaurant in a university in Finland. Life Cycle Assessment (LCA) is utilised as the tool to measure the impacts on biodiversity resulted from these meals, and to estimate the biodiversity loss. The purpose of this study is to provide evidence-based information for the consumers as well as the food service providers to help make decisions in order to reduce their individual impact on biodiversity loss by their food choices. By understanding the impacts that these different food options have on biodiversity, the consumers and food service providers can make more informed decision on their production and consumption practices.

1.3 Structure of the thesis

The second chapter provides an overview on the interrelation of the food and biodiversity, which explains the rationale of the impacts on biodiversity due to food production and consumption patterns. Followed by the briefing of the methodology, which explains LCA and its application for the biodiversity impacts assessment. Further, LCA of the food meals is initiated in chapter four, where goal and scope definition are described, and the process of life cycle inventory analysis and life cycle impact assessment is explained. Chapter five provides the results with interpretation and discussion, and the thesis is concluded by chapter six with the summary of the study.

2 Food and biodiversity

2.1 Interrelation between Food, Biodiversity and Climate change

Food production and consumption is considered as one of the significant contributors towards the reduction of biodiversity and environmental quality. Currently around world's 50% of the habitable land surface and 75% of the freshwater resources are utilised for crop and livestock production. In addition, 75% of the deforestation across the globe, accounting to around 5 million hectares per year is driven by agriculture, which is influencing the biodiversity losses. (Behnassi *et al.*, 2022)

Biodiversity and food security are intertwined in several ways, and preserving biodiversity is vital for achieving global food security and sustainability. Biodiversity is instrumental in regulating the nutrient cycles, catering clean water and diverse food supply, and in the diminution of the effects of climate change. The documentation on biodiversity can be considered biased and generally leave unnoticed the loss of genetic diversity in crops, livestock, poultry and fish species, rather spotlighting on the species experiencing existential threats. (Behnassi *et al.*, 2022) The interrelation between biodiversity, climate change and food are shown in Figure 1.

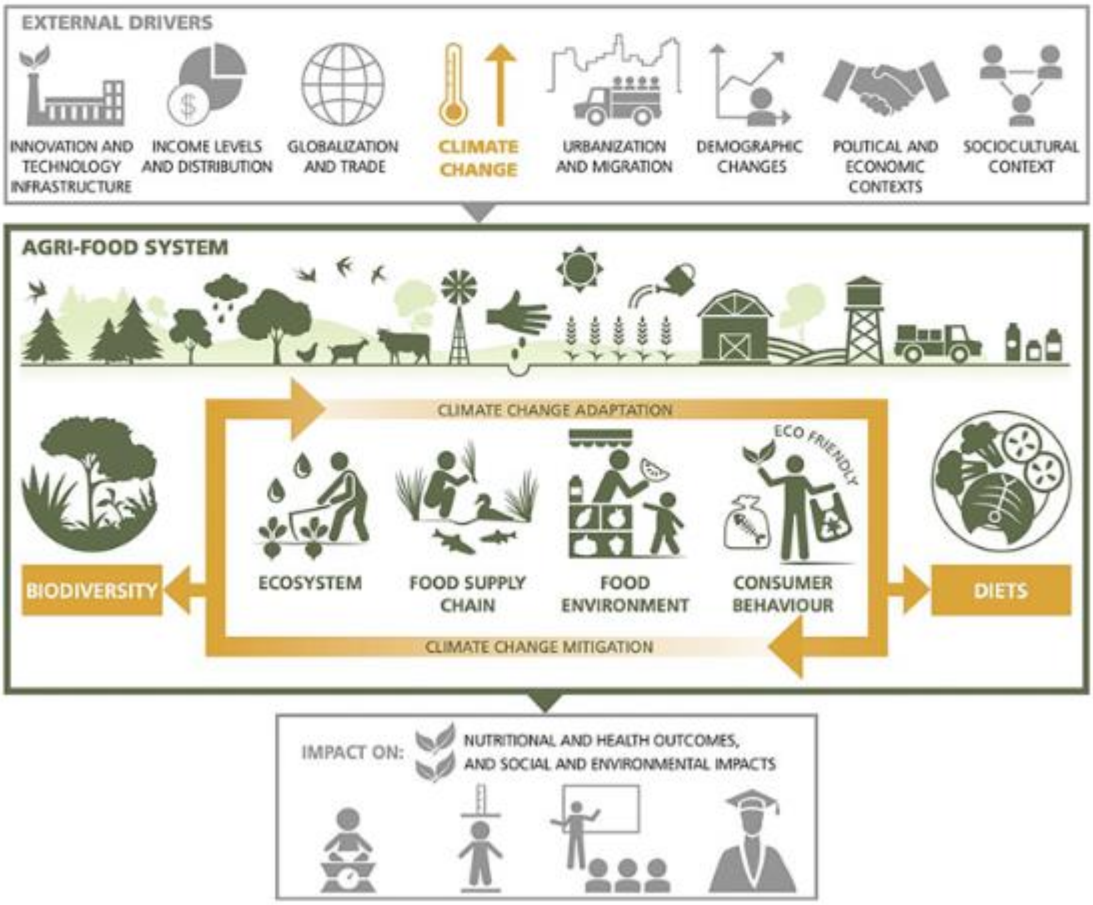

Figure 1. Nexus of biodiversity, climate change, and food (Behnassi *et al.*, 2022).

Proliferating economic competitiveness and growing financing productivity in the agriculture sector are the drivers which are serving to achieve the goals of food security locally and globally through lowering the prices of food commodities and improving the access to food. However, this development of increased food production at a lower cost has some detrimental effects on the environment and results in biodiversity loss. Financial incentives towards increasing yields are inducing unsustainable agriculture production practices. Intensive farming and abusive resource exploitation has degraded the quality of soil, air, water sources and natural ecosystems, which in turn results in increased use of pesticides and fertilizers. Such agricultural operations also contribute towards rising climate change, GHG emissions, unsustainable land use and land use change practices and escalating deforestation activities which further drives the biodiversity losses. For the purpose of reducing the negative impacts on biodiversity and to conserve it, it is vital to understand the relationship between supply and demand of food commodities and to recognize the key drivers that are inducing biodiversity loss (Benton et al., 2021). Composition of multiple factors accountable for biodiversity loss in the current food system in shown in Figure 2.

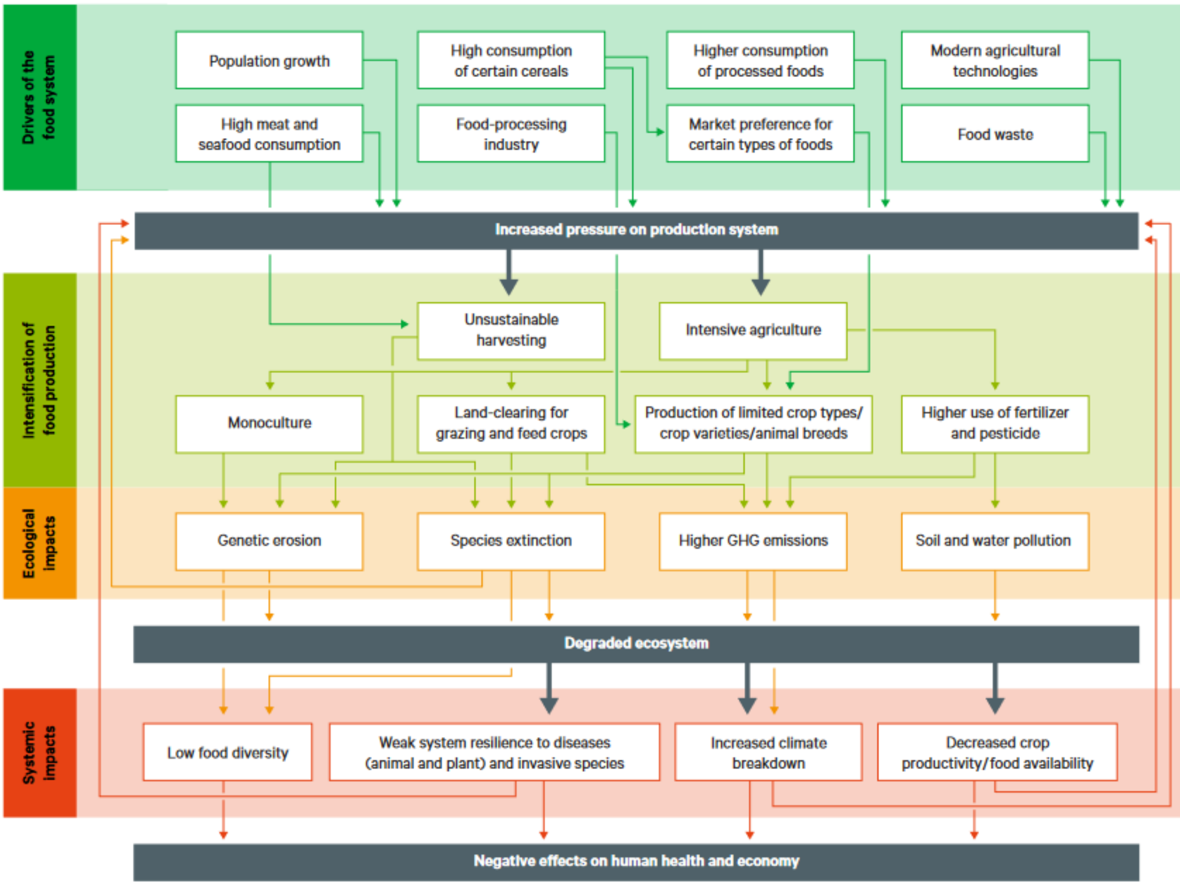

Figure 2. Food system and its impacts on biodiversity (Benton et al., 2021).

2.2 Food consumption pattern

The definition of the sustainable diets according to the United Nations Food and Agriculture Organization (FAO) are the diets that are healthy, affordable, culturally acceptable, and possessing reduced environmental impacts (Aleksandrowicz *et al.*, 2016). In recent decades, high-income countries have witnessed a transition in consumption patterns towards energy-intensive and animal-based food choices, resulting in considerable environmental degradation (Paris *et al.*, 2022). According to the Rockefeller Foundation-Lancet Commission on Planetary Health, dietary changes are necessary to enhance human health and mitigate the environmental consequences of food production (Aleksandrowicz *et al.*, 2016).

The existing practices of food production and consumption are progressively recognized as unsustainable. While they serve the essential human need for nutrition, they also pose severe environmental threats and challenges (Notarnicola *et al.*, 2017). Animal-based foods are identified as significant contributors to these environmental impacts (Aleksandrowicz *et al.*, 2016). Nonetheless, the production of all types of foods, including plant-based options, is linked to environmental impacts like climate change, eutrophication, ecotoxicity, water use, land use and others (Karlsson Potter and Röös, 2021). Current food production system incorporates the traditional industrialized high-input, high yielding agricultural practices (Chappell and LaValle, 2011). Conventional food systems are significant contributors, resulting in adverse effects on biodiversity through habitat degradation and alterations in species distribution (Behnassi and Gupta, 2022).

Within the European Union (EU), approximately 950 kg of food are consumed per person annually, contributing to around 27% of the EU's overall consumption-based environmental footprints, with animal-based products representing a significant portion of this impact. EU food consumption has implications for global greenhouse gas emissions, deforestation, and biodiversity loss, primarily stemming from agricultural imports. Farm to Fork Strategy, implemented in 2020 by EU, set forth ambitious targets to establish sustainable food systems as elements of the EU Green Deal. (Paris *et al.*, 2022)

There is growing consensus that shifting from meat and dairy-intensive diets to predominantly plant-based diets is crucial in alleviating environmental strain from the food system, which can lead to reduction in environmental impacts (Karlsson Potter and Röös, 2021; Paris *et al.*, 2022). As environmentally conscious consumers adopt vegetarian or vegan diets or reduce their meat consumption, the demand for sustainable plant-based food choices is steadily increasing. High-income countries are witnessing a surge in interest for plant-based protein sources, leading to rapid product development in ready-made meat alternatives. This trend indicates a growing number of consumers concerned about the environment are willing to alter their dietary preferences. However, studies reveal that these consumers lack sufficient information despite the abundance of research on food and diet sustainability. Therefore, there is a pressing need for easily accessible and comparable consumer information regarding the environmental impact of food products. (Karlsson Potter and Röös, 2021)

3 Methodology

3.1 LCA as a method

In the past few decades, LCA has become a global leading tool used to support the decision making in the realm of environmental sustainability. ISO 14040 and ISO 14044 standards facilitates the LCA practitioners and researchers to follow a consistent approach to carry out LCA studies. This makes the assessment process more transparent and the obtained results and findings from the study more credible, which supports the decision-making process of an individual, who can be a producer or a consumer (Owsianiak *et al.*, 2018).

LCA is a method that is used to assess the environmental impact of a product system and its supply chain throughout its different life cycle stages. The environmental impacts resulted by a product from its cradle to grave can be analysed using LCA. The life cycle stages usually include raw material acquisition, production, transportation and distribution, use or consumption, and end of life phases (Lindqvist, Palme and Lindner, 2016; Takacs *et al.*, 2022).

LCA generally contains four phases in a study: the goal and scope definition, inventory analysis, impact assessment and interpretation phases as represented in Figure 3. During the goal and the scope definition phase, the reason for carrying out the study and the intended application of the results should be established, along with the target audience of the study. There are different aspects involved with the scope of the study which shall be identified according to the goal of the LCA. System boundary is set during this phase, which determines the extent of the product system, processes and their aspects included in the study. Other aspects such as functional unit, cut-off criteria, allocation procedures, data and data quality requirements, assumptions made during the study, limitations, inclusion of optional elements such as weighting, normalization and others are considered and described during this phase. The established goal and scope and its elements can be modified due to unforeseen limitations, constraints or discrepancies in data.

The inventory analysis shall be conducted according to the guidelines provided in the standard and all the calculations shall be documented, and the assumptions made during the calculations should be reported. Processes such as data collection and validation, establishing reference flows in accordance with the functional unit and the system inputs and outputs, refining the initially set system boundary if necessary, based on the data availability with respect to goal and scope definition. Identifying the different elementary flows, allocation procedures if necessary, and any exclusions made should be reported in the life cycle inventory analysis (LCI) phase.

The potential impacts on environment and biodiversity are calculated and reported in life cycle impact assessment (LCIA) phase, in accordance with the goal and scope of the study. LCIA phase is coordinated with other phases considering the possible omissions and sources of uncertainty. The selection of impact categories, category indicators and characterization models are made based on the goal and scope of the study. The LCIA result can be of a single impact category or comprising the results of multiple impact categories. Characterization of the results is carried out based on the spatial and temporal aspects, different characterization models are equipped with their distinctive characterization factors. After the calculations, the obtained results are compiled and presented as a LCIA profile. Optional elements of LCIA such as normalization, weighting, grouping and data quality analysis are carried out if deemed necessary.

In the life cycle interpretation phase, the significant issues are identified based on the results obtained during the LCI and LCIA phases. Processes and elementary flows that contributed the most to the environmental impacts are identified. Evaluations of the methodology and the obtained results are made using different checks such as completeness, sensitivity and consistency checks. It provides information about the issues that needs to be considered with respect to spatial and temporal aspects. Conclusions are drawn out in this phase along with the limitations of the conducted study. Appropriate recommendations are made towards decision makers based on the intended application and goal of the study.

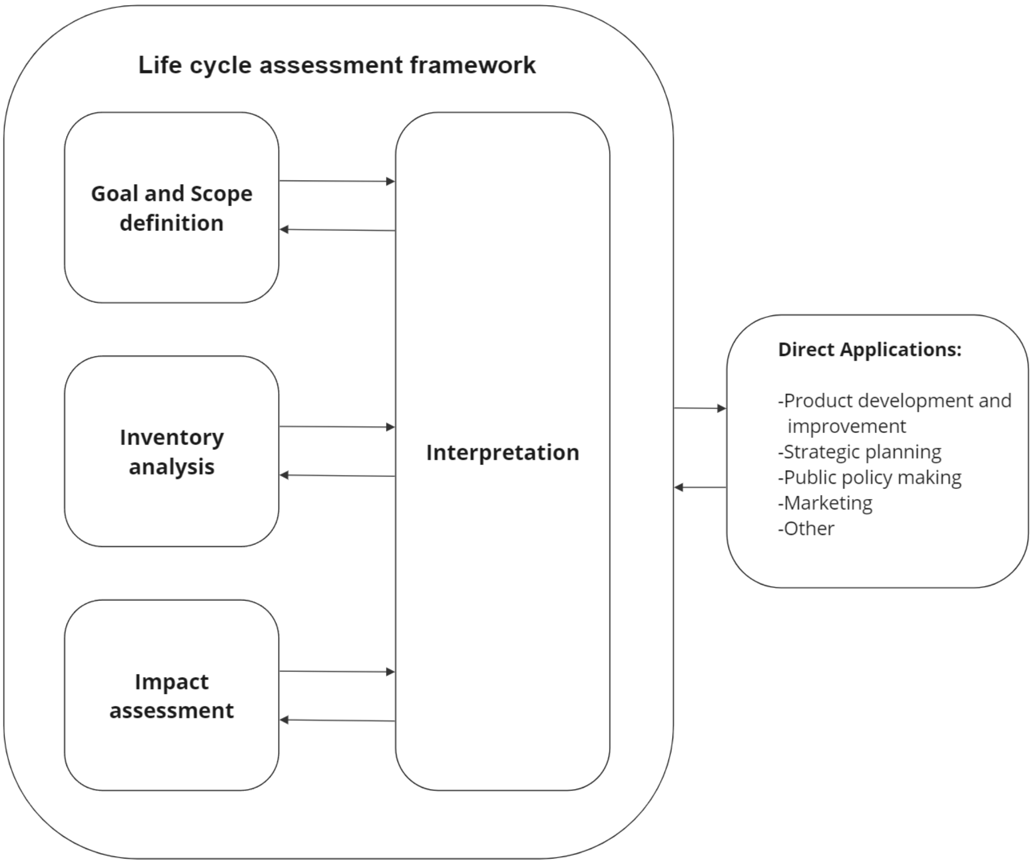

Figure 3. Stages of LCA (SFS-EN ISO 14040:2006).

3.2 LCA as an approach to assess impact on biodiversity

For the purpose of evaluating the effects of products and organizations on biodiversity, it is vital to establish scientifically sound models and indicators that can comprehensively capture the impacts on biodiversity throughout the entire value chain, in addition to identify the drivers and to design strategies to mitigate the biodiversity loss (Damiani *et al.*, 2023). One potential approach to assess impact on biodiversity is by using the LCA framework. Numerous LCA methods have been developed, each focusing on distinct biodiversity aspects, such as biotopes, plant richness, functional diversity, or the preservation of habitats crucial for biodiversity. (Klein *et al.*, 2023)

In LCA, the quantification of the different environmental loads is made during the inventory analysis phase, and then the quantified environmental loads are multiplied with the respective characterization factors (CF) during the Life cycle impact assessment (LCIA) phase to assess the contributions towards different environmental impacts such as global warming or acidification. There are different models and impact categories available for carrying out this process, and different models have different characterization factors that can be multiplied with the quantified environmental load to arrive at the desired results, e.g. to assess the impact from the land use, the total land used is multiplied with the corresponding environmental load. Impacts on the biodiversity of a product system can occur via variety of pathways, it can be the indirect impacts resulting from global warming, eutrophication, acidification, and other environmental impacts. It can also be the direct impacts resulting from land use practices. (Lindqvist, Palme and Lindner, 2016)

Among the earlier LCA studies on the impacts resulting from food production and consumption practices, a greater number have focused on midpoint indicators such as climate change, acidification, eutrophication and others, which demonstrates the impact on environment. However, newer studies have been conducted where midpoint and endpoint approach are linked and focusing on land use and water use which contributes to biodiversity loss. (Crenna, Sinkko and Sala, 2019) While endpoint modelling is acknowledged to have significant uncertainty, it can shed light on crucial aspects that warrant further examination. Endpoint modelling involves a simplified damage system constructed on scientifically based amalgamation of impact categories, simplifying the comparison and comprehension of impacts. (Crenna, Sinkko and Sala, 2019)

Various methods and models have been devised to assess biodiversity loss in the field of LCA. Among such methods and models to assess the impacts on biodiversity, some are operational and are available in LCA software's to practice, and the others are yet non-operational or are under development. The operational methods and models available on LCA software's are 'endpoint' methods and models. The non-operational methods and models can be further subcategorized into 'endpoint' and 'midpoint' methods and models. (Crenna *et al.*, 2020) The existing endpoint LCA models to measure the potential biodiversity impacts are given in Table 1.

Table 1. Examples of currently operational LCIA endpoint methods for biodiversity impact assessment (Crenna *et al.*, 2020)

LCIA method	**Impact categories for biodiversity**	**Metric/indicator of impact**	**Spatial resolution of impact assessment**	**Relation to categories of EBVs**
ReCiPe 2016	climate change (terrestrial and freshwater ecosystems), photochemical ozone formation terrestrial acidification freshwater eutrophication freshwater, marine, and terrestrial ecotoxicity land use water use (terrestrial and freshwater ecosystems)	potentially disappeared fraction (PDF) of species over time (years)	country, global	community composition
LC-impact	climate change (terrestrial and freshwater ecosystems) photochemical ozone formation terrestrial acidification freshwater and marine eutrophication freshwater, marine, and terrestrial ecotoxicity land stress water stress	PDF of species over time (year)	country, ecoregion, global	community composition
Impact world+	climate change (ecosystem quality) freshwater and terrestrial acidification freshwater and marine eutrophication land transformation and occupation for biodiversity water availability freshwater ecotoxicity interim: photochemical ozone formation terrestrial and marine ecotoxicity ionizing radiations	PDF of species over time (year)	country, ecoregion, global	community composition
Stepwise	global warming (fossil/ nonfossil) photochemical ozone – vegetation terrestrial acidification terrestrial and aquatic eutrophication terrestrial and aquatic ecotoxicity nature occupation	biodiversity adjusted hectare year (BAHY)	global	community composition
EcoScarcity 2013	biodiversity damage potential through land use	Eco-points	country, global	community composition

3.3 Limitations of existing LCA methods

There are several limitations regarding the current life cycle-based metrics and indicators used to assess the impacts on biodiversity of a value chain, and so far there exists a lack of universal approach. Latest evaluations regarding the incorporation of biodiversity into life cycle assessment (LCA), particularly within the life cycle impact assessment (LCIA) framework, have outlined a series of recommendations for advancement in the field. As of now, LCA studies involves a handful of aspects related to biodiversity, such as extinction rate and species richness, which are identified at species level. The frequent recommendations received in this regard are as follows, "(i) to incorporate more dimensions of biodiversity (which will probably require several indicators), (ii) to cover more drivers of biodiversity loss (habitat change through land use has been the most addressed driver), and (iii) to include spatial detail in biodiversity impact assessments" (Crenna *et al.*, 2020).

The impact categories available in currently operational LCIA models employ only a portion of the factors contributing towards biodiversity loss. The existing midpoint and endpoint impact categories constitute only four out of five drivers of biodiversity loss recognised by the Millennium Ecosystem Assessment which are "habitat alteration, climate change, pollution, resource overconsumption and biotic exchange in terms of spread of invasive species". (Crenna, Sinkko and Sala, 2019)

It has been emphasized that the current metrics used for biodiversity impact assessment in LCA are inadequate in capturing the intricate nature of biodiversity or are not fully operational to be equipped by LCA practitioners. This highlights the insufficiency of the present LCA framework to effectively guide decision-making based on available biodiversity indicators. (Crenna *et al.*, 2020)

Pereira et al., 2013 defines Essential Biodiversity Variables (EBVs) which was inspired by the Essential Climate Variables (ECVs) as the metrics that are essential for the study, reporting, and effective management of biodiversity changes. There are six general classes of EBVs considered for biodiversity metrics: genetic composition, species populations, species traits, community composition, ecosystem structure, and ecosystem function. Hence, it is emphasized to incorporate these aspects in the biodiversity assessment models. (Pereira *et al.*, 2013)

A detailed study was conducted by (Damiani *et al.*, 2023) covering 17 LCA based models with an objective of assessing the advancements made in developing models and methodologies for analysing biodiversity impacts within the context of LCA. This was approached by examining each method's incorporation of the number of pressures, types of ecosystems, taxonomic groups, essential biodiversity variable classes (EBVs), and fundamental biodiversity aspects within its scope of analysis. Based on this analysis, only 4 out of 17 LCA based methods performed well for the “ecosystem” criteria, among which, only 3 methods are operational. ImpactWorld+ method was the best method in terms of taxonomic coverage, covering 15 taxonomic groups. However, even the most comprehensive methods that consider taxonomic groups incorporate only a fraction of the known and undiscovered biodiversity. Therefore, enhancing biodiversity coverage concerning taxonomic groups remains a critical aspect to address in the pursuit of improving biodiversity assessments. Concerning EBVs, the biodiversity metrics predominantly focus on the "community composition" class of EBVs, primarily utilizing species richness indicators (e.g., PDF). However, the other EBV classes receive less attention in these methods, leading to limited consideration of crucial biodiversity aspects like genetic composition, species traits, and ecosystem functioning. It is mentioned that there is lack of robustness among the impact models, which should be considered while selecting the most suitable method for the study. (Damiani *et al.*, 2023)

3.4 Database and Software

The recent advancements in the process-oriented life cycle inventory databases have resulted in the development of different food related databases encompassing the overall agricultural supply chain. These databases include the World Food LCA Database, which has been integrated into ecoinvent, Agribalyse Database and the Agri-footprint database. (Jolliet, 2022)

The database used for this study is Agribalyse. It is a French database, which comprises of public Life Cycle Inventories (LCI) of numerous agricultural products. The database was initially published in 2014 and is periodically updated. The French Environment and Energy Management Agency (ADEME) along with 14 other research and technical institutes contributed towards building a collective homogenous LCI database for the agricultural products originating from France, in addition with some imported products. (Colomb *et al.*, 2015) Relevant data from other databases (e.g., ecoinvent, SimaPro, WFLDB) and from literature is also integrated in Agribalyse (Koch and Salou, 2022). The version of the database used for this study is v3.0.1.

Several software's such as SimaPro, GaBi, COMPASS, openLCA, Umberto NXT, etc., are available to carry out LCA analysis. Different software's employ datasets from various databases available. Studies have shown that the results provided by the different LCA software's can vary for the same inputs, even when a common methodology is adopted for the study. (Speck *et al.*, 2015, 2016; Aparecido Lopes Silva *et al.*, 2017) In this context, openLCA offers ease of access and it is compatible with the database chosen for this study, hence it was chosen to execute this LCA analysis. The version of the software used is openLCA v. 1.11.0.

3.5 LC-IMPACT method

The LC-IMPACT method offers endpoint characterization factors (CFs) for 11 impact categories, with 7 of them being related to ecosystem quality, specifically biodiversity loss (in PDF·y). The level of regionalization in LC-IMPACT varies depending on the impact category. For biodiversity-related impact categories, spatial differentiation is considered. For example, photochemical ozone formation considers world regions, toxicity considers subcontinental regions, acidification considers a resolution of 2° × 2.5°, freshwater and marine eutrophication consider freshwater ecoregions, river basins to large marine ecosystems, land stress considers terrestrial ecoregions, and water stress considers a resolution of 0.05° × 0.05°. Apart from CFs at native scales, LC-IMPACT also provides averages for countries, continents, and the global scale. (Verones *et al.*, 2020)

The LC-IMPACT diverges from the traditional perspectives that are generally used in LCA such as individualist, hierarchist and egalitarian approaches. On the contrary, the characterization factor is structured in a modular fashion, offering users the flexibility to include or exclude impacts that are more distant in time and less definitively attributed to a particular impact category (Verones et al., 2020). Accordingly, the method offers four sets of CFs for the user as mentioned in the Table 2.

Table 2. Different sets of CFs provided in LC-IMPACT.

Category	Description
All impacts, 100 years	short time horizon and high level of certainty for impact of a specific intervention
All impacts, long term	long time horizon and high level of certainty for impact of a specific intervention
Certain impacts, 100 years	short time horizon and low level of certainty for impact of a specific intervention
Certain impacts, long term	long time horizon and low level of certainty for impact of a specific intervention

Impact categories employed for conducting LCIA for this study is mentioned in the section 4.3 of the report. Modelling approach, taxonomic coverage and spatial scales included in LC-IMPACT method, attributed to the impact categories addressing the ecosystem quality, which are considered in this study for the assessment of biodiversity loss are given in the Table 3.

Table 3. Summary of impact categories addressing ecosystem quality (Verones et al., 2020)

Impact category	Modelling approach	Taxonomic coverage	Native spatial scale
Climate change (terrestrial ecosystems)	Mix marginal/average	Mammals, birds, frogs, reptiles, butterflies, vascular plants	Global
Climate change (freshwater ecosystems)	Mix marginal/average	Fish	Global
Land stress	Both marginal and average	Mammals, birds, reptiles, amphibians, vascular plants	804 terrestrial ecoregions
Water stress (ecosystems)	Marginal	Mammals, birds, reptiles, amphibians, vascular plants	0.05º x 0.05 º

4 LCA: Biodiversity assessment of selected meal options

4.1 Goal and scope definition

4.1.1 Goal

The primary goal of this study is to assess and compare the impacts on the biodiversity caused by the consumption of different types of individual meals involved in this study, which are served at an institution in Turku, Finland. The whole life cycle stages of the meal, including the supply chain of the ingredients of the meals are considered for the impact assessment in this study. Life cycle assessment is used as the method to assess the impacts arising from the meal's different life cycle stages. The obtained results of different meals will be used to compare the biodiversity impacts of different category of meals and to convey the same to the consumers and food service providers.

The secondary goal of this study is to assess the environmental impacts of the meals under the study and to compare the results of the different category meals, also to understand the correlation between the impacts on environment and biodiversity.

4.1.2 Meals

The meals included in the analysis and their category are given in the Table 4. The authentic recipes of the meals included in the study were sourced from correspondence with the food service provider. A total of six meals were chosen for the study. The meals from different category were chosen for the comparison: different meat based (3 different meats), vegetarian, vegan and plant-based meat substitute.

Table 4. Different types of meals included in the analysis.

Meal Category	**Meal**
Meat based (Beef)	Beef lasgna
Meat based (Chicken)	Lemon broiler chicken
Meat based (Pork)	Pea soup with pork
Plant based meat alternative (Tofu)	Pea sop with tofu
Vegetarian	Spinach Crepe
Vegan	Vegan casserole

4.1.3 Definition of different categories of meals

The scope of this study includes different categories of meals in the analysis as mentioned in Table 4. Each category of meals has certain variations to it based on the type of ingredients used for the meals. The exclusion and inclusion of different types of ingredients in the meals included in this study is briefly explained below:

- Meat based: The recipe traditionally includes different kinds of meat, for example: beef, pork, chicken, etc. It can also include dairy products and it may include plant-based ingredients or sometimes it may not include them.
- Vegetarian: This type of recipes normally does not include any meat it. However, it includes all kinds of plant-based ingredients. it can also contain animal-based products such as dairy and eggs.
- Plant based meat alternative: This recipe is similar to the meat-based meal, but the traditional animal-based meat is replaced with the meat processed using plant based derivates.
- Vegan: In vegan recipes, all kinds of animal-based ingredients are excluded. So, the vegan meals do not contain any types of meat. eggs, dairy and even fish. It only contains all kinds of vegan ingredients. (Takacs *et al.*, 2022)

The key differences between the variations in the ingredients of the different meals is given Table 5.

Table 5. Primary variations in the ingredients used for different categories of meals included in the study.

Ingredients	**Meat based**	**Vegetarian**	**Plant-based meat**	**Vegan**
Animal based meat	✓	✗	✗	✗
Fish & Seafood	✓	✗	✗	✗
Eggs & Dairy	✓	✓	✗	✗
All plant based products	✓ or ✗	✓	✓	✓

4.1.4 Definition of functional unit

As food is multi-functional, it would be impractical to associate its functions and benefits to a single variable. Hence, the earlier studies related to LCA of food have used a wide variety of functional units such as per kg or 100 g, per kcal, per serving, per meal or per person per day for an entire diet. (Jolliet, 2022)

In this study, it is assumed that the meals served to the consumers have the same purpose of providing lunch for the consumers, and all the meals are considered to be comprising of adequate nutritional values. In this case, the functional unit based on the nutritional values of the meals can be considered more rewarding in terms of the results obtained.

However, in general the consumers enter the food providing facility with an intention of choosing a meal to consume based on their preference type of meal and rather not with the intention of consuming a specific amount of nutrients such as calories, proteins, and other nutrients of any meal (Takacs *et al.*, 2022). So, the functional unit was considered to be the portion size of a single meal provided by the food service provider. The quantities of the functional unit for each meal in given in Table 6. Based on the recipes, the mass of a single meal of the different meals included in the study varied, as well as the quantity of the ingredients used for the preparation of the meals.

The mass based functional unit allows the ease of calculating the impacts on biodiversity and the environment caused due to the consumption of these meals compared to the nutrition based functional unit. In addition, it also offers better understanding of contribution of the various ingredients of the meals in the overall impacts on biodiversity and environment. (Takacs *et al.*, 2022)

Table 6. Quantities of the single serving portion of the meals.

Meal	**Quantity (in grams)**
Beef lassgne	500
Lemon broiler chicken	480
Pea soup with pork	450
Pea soup with tofu	400
Spinach Crepe	430
Vegan casserole	400

4.1.5 System Boundary

The system boundary for this case of LCA of different category of meals is considered to be from cradle (raw material acquisition) to plate (food consumption). The different phases included in the system boundary of an individual meal are agricultural production, ingredient processing, packaging, transportation and waste management during different phases applicable, distribution, storage, and meal preparation. The system boundary is considered to be same for all the different meals included in the study. A short description of each stage is given below. Figure 4 shows the system boundary of the study.

4.1.5.1 Agricultural Production

This is the stage where the food crops and animals are produced, and the inputs considered are the agricultural equipment and machinery (used for fertilization, hoeing, ploughing, harvesting and other procedures), chemical products used to aid the cultivation (e.g., fertilizers, pesticides, herbicides, fungicides, and others), animal feed production, water used for irrigation, fossil fuel and energy consumed, also other resources used.

4.1.5.2 Ingredient Processing and Packaging

In this stage the food crops and animal products are further processed and transformed into ready to use ingredients, such as ready vegetables, meat and dairy products, sauces, jams and others. The produced ingredients will undergo their respective packaging process with suitable packaging materials. The water, energy, packaging and the other resources consumed during both the production and packaging processes are considered.

4.1.5.3 Transportation and Waste Management

Transportation of the products throughout the different life cycle stages are considered, three different modes of transportation involving road, rail and waterways are included in the study. The vehicles and the fossil fuels use are considered for transportation. Waste management is included in those processes where it is applicable. Biowaste and recyclable wastes are sent for composting and recycling respectively, and the other wastes are sent for landfilling. The wastewater generated during different process will undergo further treatment.

4.1.5.4 Distribution and Storage

The ready to use ingredients are assumed to be distributed to supermarkets where they will be stored, the energy and the other resources used during these processes are considered for the study.

4.1.5.5 Meal Preparation

During the meal preparation (cooking) phase, only the water and electricity consumed is considered in the study, the tools and appliances used for meal preparation are not included in the study. Food waste and packaging waste generated after the human food consumption, wastewater generated during cleaning of the vessels, consumption of other resources such as cleaning agents, utilization of electricity for the lighting and other purposes during the food consumption are not considered within the scope of the study.

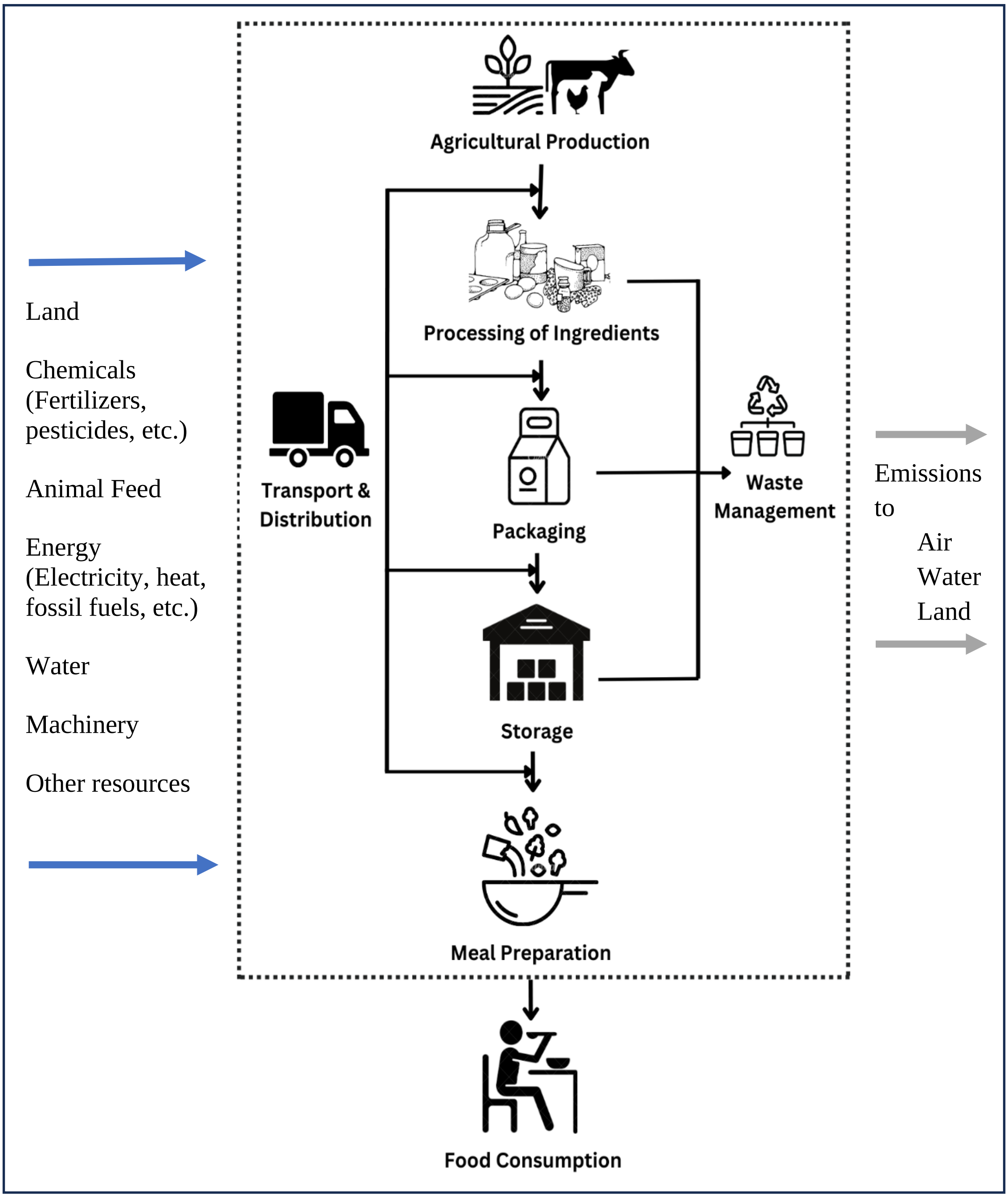

Figure 4. System boundary used for this study for the LCA of meals.

4.1.6 Cut Off Criteria

In the standard ISO 14044:2006 Life cycle assessment — requirements and guidelines, which provides different strategies to make the assessment procedure more simpler, it is suggested that the cut off rules can be used to exclude the life cycle stages that are less relevant for the particular study or to have reduction in the number of inventoried data, provided that the assumptions made for choosing the cut off criteria is clearly stated in the assessment and it allies with the goal of the assessment. (Gomes Silva *et al.*, 2020) (SFS-EN ISO 14044, 2006)

For this study, two cut off rules were considered. The ingredients from the recipes which contribute less than 1% to the total mass input for the unit process (meal) have been excluded from the study. The total mass of the excluded ingredients for each individual meal is not more than 5% of the total mass of the overall individual meal. The share of mass of the ingredients excluded from different category of meal from the total mass of the meal is shown in the Table 7.

Table 7. Share of mass of ingredients excluded from the meals for the study.

Meal	**Excluded ingredient mass from the meal**
Beef lasgna	1.70%
Lemon broiler chicken	2.80%
Pea soup with pork	1.29%
Pea soup with tofu	1.36%
Spinach Crepe	2.18%
Vegan casserole	1.54%

4.1.7 Assumptions

The choices and assumptions made during the goal and scope definition concerning the parameters and scenarios can have significant effect on the end results of the study and may cause several uncertainties (Rivera and Sutherland, 2015; Takacs *et al.*, 2022). For the comparison of different LCI results, assumptions made must be in line. (SFS-EN ISO 14044, 2006) Some of the assumptions made for this LCA study are described in this section.

Majority of the ingredients that are used for the meals in the study are considered to be originating from Finland. For those ingredients that are not practically feasible to be originating from Finland, it is considered that they are from global origin. All the food crops are grown conventionally and not using organic farming. It was assumed that the energy used for different processes, including both electricity and heat are generated using conventional energy resources and not using renewable energy resources. For transportation, the conventional fossil fuels are used and there are no electric vehicles used for transportation. Supermarkets were considered to be the intermediate storage option for the ingredients instead of on-site storage or industrialised options, this was to simplify data collection as the storage data was readily available in the database. It was assumed that the impacts during and after the human food consumption would be minimal, and hence the phase was not considered under the scope and system boundary of the study. Several other assumptions have been made pertaining to the subsequent sections, which will be further described in those respective sections.

4.2 Life Cycle Inventory Analysis

4.2.1 Data collection

The varieties and amounts of ingredients utilized in each recipe were sourced from recipe cards supplied by the institutional food service provider. Due to the consideration of cut off criteria mentioned in the section 4.1.6 , ingredients comprising less than 1% of the total weight of each recipe (such as spices, salt, garlic, pepper and others) were omitted from the life cycle assessment (LCA) of the meal. The main ingredients and their quantity used for the respective meals which were used for the LCA analysis are provided in appendices. The ingredient quantities provided are for the function unit of serving portion size of the meals. The remaining ingredients that were excluded from the study are not provided in this section due to confidentiality reasons. The inventory quantities provided are the raw weight of ingredients before meal preparation and not the weight of the ingredients incorporated in the prepared food.

As there was lack of data for some of the ingredients in database, those ingredients from the original recipes have been replaced by similar ingredients whose data was available and the characteristics of the replaced ingredients are closely related to the ones replacing them in the recipes. For instance, one of the recipes had consisted of Lingonberry jam for which data was lacking, instead it was replaced by Raspberry jam, whose data can be considered closest to Lingonberry jam among the available alternative ingredients. Data of some of the ingredients in the Agribalyse database is a derivative of other similar ingredients and contains the same input values with different ingredient names. For example, Raspberry-Strawberry, Kale-Cauliflower, Sweet Potato-Potato, here the prior mentioned ingredient reproduces the input data of the later mentioned respective ingredients in the database.

Collection of actual primary data related to ingredient processing, packaging, transport and distribution, storage and waste management for all the ingredients was a tedious task. Hence, it was assumed that the processes and data available in the Agribalyse database shall be used for the study as majority of the data available in the database is from France which has practically similar conditions that resembles Finland as both the countries are constituents of Europe. The input data includes transport distances, modes of transportation, energy and resource consumption for different processes, packaging, storage, waste management and others.

For the crops that were assumed to be originating from Finland, the yield of the crops was considered from Finland in the inventory inputs, and for the ingredients that was practically not feasible to be originating from Finland, it was assumed that they were imported to Finland from the countries or regions as per the data available in the database. The yields of the crops originating from Finland are for the year 2022. The appliances necessary for the preparation of the meals are not part of the inventory, only the electricity consumption during the cooking and baking time was considered. The cooking and baking time for the meals were taken by the recipe cards provided by the food service provider. Electricity consumption for the meal preparation process was taken from the literature in addition to the data available in the database.

4.2.2 Data Sources

Different data sources were used for the study. Major part of the background data for the study was used from the Agribalyse database version 3.0.1, and part of the data was collected from the statistics published by the Natural Resources Institute Finland (LUKE). Foreground data used in the study was predominantly collected by the food service provider through correspondence, and part of the foreground data was collected from the literature and Agribalyse v 3.0.1 (Table 8).

Table 8. Data sources used for the study.

Life Cycle Stage	Parameter	Source
N/A	Recipes	Primary data: Food service provider
Agricultural production	Ingredients (inventory of inputs to produce the ingredients such as machinery, pesticide, fertilizers, etc.,)	Agribalyse v3.0.1,
Processing, Packaging, Transportation and distribution, Storage, Waste management	Transport distances and modes, vehicles and fuel used for transportation, material and energy consumed for ingredient processing, packaging, storage, and waste management (respective inventory items)	Agribalyse v3.0.1, Natural Resources Institute Finland (LUKE)
Meal preparation	Time required for meal preparation, energy consumed for meal preparation	Primary data, Agribalyse v3.0.1, (Calderón *et al.,* 2010)

4.2.3 Allocation

Allocation method is used to partition or proportionate the input and output flows of the unit process of a product system. Allocation is used when there is multiple products or co-products. Allocation procedure can be carried out based on different parameters such as physical properties (e.g. mass, volume) and economic value (e.g. market value) of the products and co-products. (SFS-EN ISO 14040, 2006)

However, allocation for a product system related to agriculture and food is rather complex as it involves consideration of several factors. Further, allocation for products and co-products in the Agribalyse database is based on different parameters and methods for handling products and co-products, such as economic values, bio-physical values, mass, weight, growth and others. There are also instances where no values were allocated to a certain product or a co-product. The allocating procedures adopted for the database are further explained in the methodology of Agribalyse. (Koch and Salou, 2022) Due to the intricacies involved in the allocation procedures, the allocation method used for this LCA study is the default allocation values that are defined in processes.

4.3 Life Cycle Impact Assessment

Life cycle impact assessment (LCIA) includes mandatory elements and optional elements. The mandatory elements of the LCIA phase includes procedures such as, choosing the impact categories, assigning the LCI results to the impact category (classification), choosing the characterization model and category indicators, calculating the category indicator results using the characterization factors (characterization). The optional elements include normalization, grouping, weighting and data quality analysis. However, the optional elements in the LCIA study are carried out based on the requirement specified in the goal and scope of the study. (SFS-EN ISO 14044, 2006) For this study, optional elements such as normalization, grouping and weighting are excluded from the study as they are not essential in line with the goal and scope of the study.

4.3.1 Biodiversity LCIA

The LCIA study was conducted using openLCA v. 1.11.0 software and Agribalyse database v3.0.1. The LC-IMPACT method with endpoint indicators was used to assess the impacts on the biodiversity resulting from the food meals. While considering the biodiversity loss and environmental impacts generated from food systems, land use is one of the major drivers in addition with climate change and wate use. (Karlsson Potter and Röös, 2021; Takacs *et al.*, 2022) Hence, the endpoint impact categories for the assessment of biodiversity loss were considered to be climate change (both terrestrial and aquatic ecosystems), land stress (terrestrial ecosystem) and water stress (aquatic ecosystem). The evaluation was conducted over a time horizon of 100 years. The characterization factors of LC-IMPACT considered for the calculation was from the value choice category of “all impacts, 100 years”. The summary of value choices included per impact category chosen for this study is provided in the Table 9.

Table 9. Overview of value choices per impact category (Verones *et al.*, 2020).

Impact category	**All impacts, 100 years**
Climate change (terrestrial ecosystems)	Time horizon: 100 years Included effects: all species included
Climate change (freshwater ecosystems)	Time horizon: 100 years Included effects: impacts on fish below 42° latitude
Land stress (occupation)	Time horizon: not relevant Included effects: occupation of six land use types
Land stress (transformation)	Time horizon: 100 years Included effects: transformation of six land use types
Water stress (ecosystems)	Time horizon: not relevant Included effects: surface water and groundwater consumption impacts on wetlands

As the LC-IMPACT method is not directly available in openLCA v. 1.11.0 for operation, the model was run on openLCA software using the ReCiPe 2016 endpoint(H) method to generate the LCI results. The CFs for the LC-IMPACT method was acquired from SimaPro software in Microsoft excel format. Further, the LCI results were downloaded from openLCA in the form of Microsoft excel, these LCI results were multiplied with the characterization factors of the LC-IMPACT method to obtain the LCIA results.

Since the chosen impact categories are measure of the damage to ecosystem qualities, the results are mentioned in terms of global fraction of potentially disappeared species over the years (PDF.years). For the results of climate change (TE and AE), the flows contributing more than 1% to the inventory results was used. All the available land flows were considered to enhance coverage of inventory flows associated with land stress (including occupational and transformation flows). For the water stress, only the blue water for irrigation was considered, i.e., the flows related to irrigation water where the water is sourced from surface or groundwater resources, this is because the majority of the global blue water consumption is due to irrigation. The flows contributing less than 1% of the inventory was excluded and the flows related to energy production, processing and other activities were also left out of the impact assessment for water stress. Subsequently the respective flows from the inventory were matched with their characterization factors from LC-IMPACT to obtain the impact assessment results. However, for some of the land stress flows such as industrial and traffic related land use, there were no matching CFs available in LC-IMPACT method. Hence, to calculate the results of such flows, CF of the highest level, i.e., urban land use change CF was considered.

During the calculation of climate change impacts the biogenic carbon dioxide flows were excluded from the LCIA as there are no related CFs available in LC-IMPACT. Regionalised CFs are available for the calculation of land stress and water stress in the LC-IMPACT method. The regionalised CFs of Finland were used to calculate the impact of the ingredients originating from Finland, and the global average CFs were used to calculate the impacts of the ingredients originating outside from Finland respectively.

4.3.2 Environmental LCIA

The inventory results were characterized using ReCiPe 2016 midpoint method with hierarchist model for the assessment of environmental impacts occurring from the food meals over a time horizon of 100 years. The midpoint impact categories chosen for the study are: Global warming, Land use, Water consumption, and Freshwater eutrophication. As these four environmental impact categories are widely utilized in evaluating and comparing the environmental impacts of food products (Mazac, Järviö and Tuomisto, 2023). In addition, Climate change as a consequence of greenhouse gas emissions, habitat loss due to land use and water use, pollution resulting from eutrophication can be considered as the significant environmental pressures associated with agriculture and food production (Belgacem *et al.*, 2021). Description of the midpoint indicators used for the study is provided in Table 10. The LCIA to acquire the environmental impacts resulting from the meal options was conducted directly on the openLCA software. Default inventory results and characterization factors of ReCiPe 2016 method were used to calculate the environmental impacts.

Table 10. Summary of the midpoint impact categories (Huijbregts *et al.*, 2017).

Impact Category	**Indicator**	**CFm**	**Unit**
Climate change	Infrared radiative forcing increase	Global warming potential (GWP)	kg CO_2-eq to air
Land use	Occupation and time-integrated land transformation	Agricultural land occupation potential (LOP)	$m^2 \times yr$ annual cropland-eq
Water use	Increase of water consumed	Water consumption potential (WCP)	m^3 water-eq consumed
Freshwater eutrophication	Phosphorus increase in freshwater	Freshwater eutrophication potential (FEP)	kg P-eq to freshwater

4.4 Sensitivity analysis

The robustness and credibility of the results obtained from an LCA study can be influenced by various factors. Therefore, it is crucial to gain a deeper understanding of their reliability. Sensitivity analysis plays a significant role in assessing how sensitive the results are to different input parameters, which, in turn, helps to identify areas where improvements in the data quality might be necessary. By spotting the most influential parameters on the end results, sensitivity analysis strengthens the overall reliability of the results. (Takacs *et al.*, 2022)

In this study, contribution analysis was carried out to identify the ingredients with the highest contributions towards biodiversity impacts. Subsequently, sensitivity analysis was conducted to gauge the impact of changes in various input parameters, consideration of the flows and characterization factors on the results.

5 Results and discussion

The outcomes of the life cycle impact assessment are presented and depicted in the following sections. Firstly, the environmental impacts resulting from the food meals at midpoint, generated using ReCiPe 2016 method, then the biodiversity impacts of the food meals at endpoint, characterized using the CFs from LC-IMPACT method.

For the simplification of the visualization of the results, abbreviations are used to represent different food meals, which is as follows: Beef lasagne (BF), Lemon broiler chicken (LBC), Pea soup with pork (PSP), Pea soup with tofu (PST), Spinach crepes (SC), Vegan casserole (VC).

5.1 Environmental impacts

The environmental impacts of the six varieties of meals are provided in this section. The main objective of providing the environmental impact results was to establish a correlation between the environmental and biodiversity impacts of the meals, and to compare the results with earlier similar studies. The relative difference in environmental impacts between meals is used to compare and quantify the variations in the results. Figure 5 shows the environmental impacts of the different types of meals included in the study for the four selected midpoint impact categories. While comparing the environmental impacts from the food meals, the meat-based meals are having significantly high impacts than the meals that are comprised of plant-based ingredients and derivatives across all the four impact categories. Beef lasagne accounts for the highest impact from climate change and land use impact categories, while lemon broiler chicken results in the highest impact for water consumption and freshwater eutrophication categories. Among all the food meals, beef lasagne and lemon broiler chicken dominate the environmental impacts across all the impact categories, while pea soup with tofu has the least environmental impacts, and the impacts of pea soup with pork, spinach crepes and vegan casserole varies accordingly across different impact categories. The results are in line with similar studies (Notarnicola *et al.*, 2017; Takacs *et al.*, 2022).

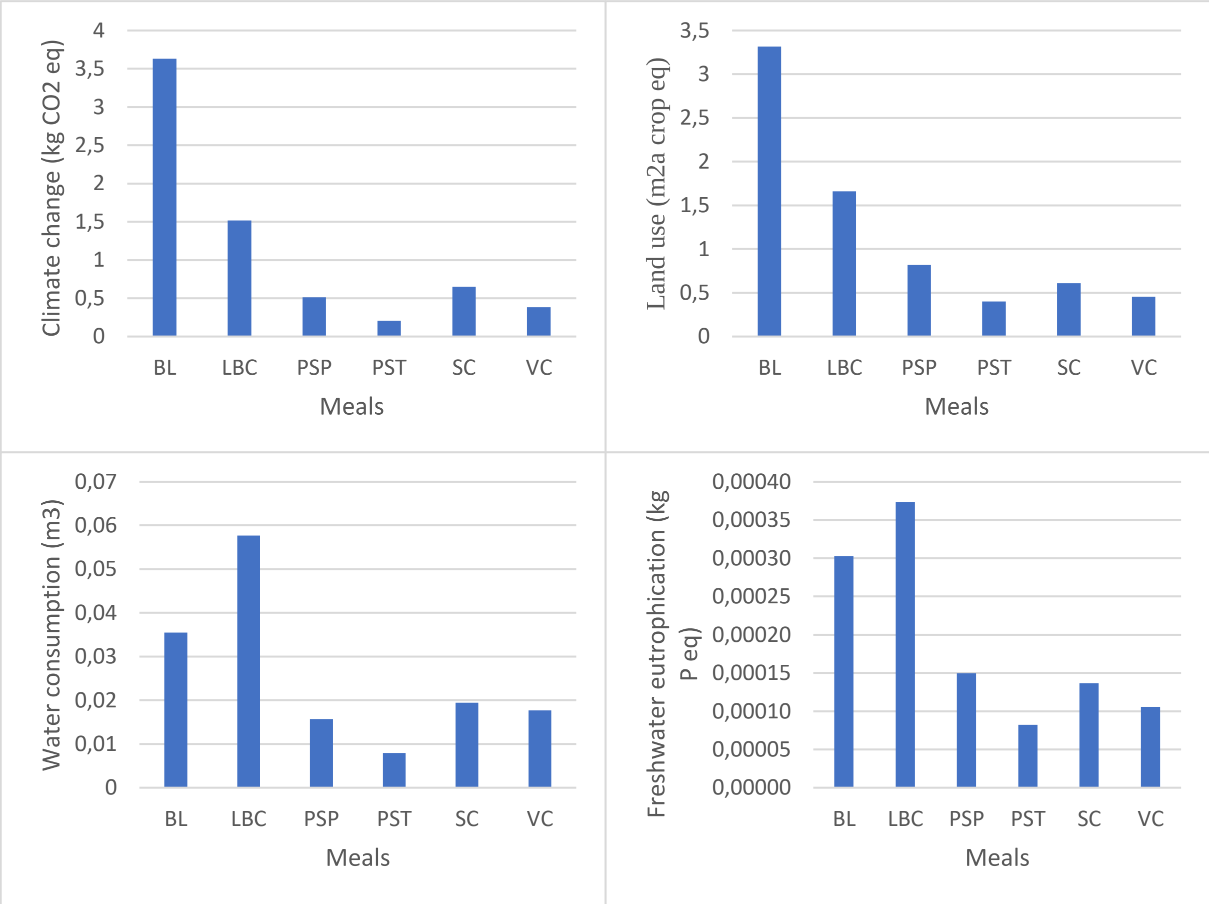

Figure 5. Environmental impacts of the different types of food meals included in this study (meat based, plant based meat alternative, vegetarian and vegan meals).

Ranking of the meals can be made based on their environmental impacts across different impact categories. The ranking method was adopted from (Takacs *et al.*, 2022). The meals were ranked from 1 to 6, 1 was allotted to the meal with the lowest environmental impact for the corresponding impact category, then 2 to the second lowest and 6 being the highest impact. The scores from different impact categories were added for the meals to obtain total score. The final ranking was based on the total score achieved by the meal, the lower the total score, the lesser environmental impacts the meal possess. The ranking of the meals is provided in Table 11.

Table 11. Ranking of the meals according to their environmental impacts.

Meals	Climate change	Land use	Water consumption	Freshwater eutrophication	Total score	Final ranking
PST	1	1	1	1	4	1
VC	2	2	3	2	9	2
PSP	3	4	2	4	13	3
SC	4	3	4	3	14	4
LBC	5	5	6	6	22	5
BL	6	6	5	5	22	6

The total scores were tied between beef lasagne and lemon broiler chicken. In this case, the individual impacts for each category were compared. While the environmental impacts from beef lasagne for climate change and land use were 58% and 50% higher than that of the lemon broiler chicken. The impacts from lemon broiler chicken were 38% and 19% higher for water consumption and freshwater eutrophication than that of the beef lasagne impacts. Hence, beef lasagne was ranked with 6, i.e., the meal having highest environmental impacts among all the food meals. The final ranking of the meals aligns with the LCA study of food meals by (Takacs *et al.*, 2022), for which similar type of meals were considered, except pork as an ingredient in their meal choices.

5.2 Biodiversity impacts

The impacts on biodiversity resulting from the six different meals with respect to the chosen endpoint categories are provided in this section. Figure 6 illustrates the LCIA results obtained with respect to biodiversity impacts for the three endpoint categories, from the meals. The results for climate change consists of the impacts on both terrestrial and aquatic ecosystems, whereas land stress accounts only for the impacts on terrestrial ecosystems, and water stress accounts for the impacts on aquatic ecosystems.

The relative results of the meals for different impact categories varies. However, highest impact on the biodiversity is caused by the meat-based meals for the chosen impact categories. Beef lasagne and lemon broiler chicken contributes substantially towards the impacts in all impact categories. The highest impact for climate change, including both terrestrial and aquatic ecosystems are resulted from beef lasagne, whereas highest impact for land stress and water stress can be attributed to lemon broiler chicken. Pea soup with pork results in the least impacts among the meat-based meal options. In fact, pea soup pork has lesser impacts than spinach crepes for climate change impact category for both the ecosystems, while it has higher impacts for land stress and water stress. Impacts resulting from vegan casserole, are considerably lower than that of the meat-based meal options. However, in comparison with spinach crepes the vegan casserole has slightly lower impacts for climate change, and higher impacts when it comes to land stress and water stress. However, vegan casserole also has higher impacts than pea soup pork for water stress. Pea soup with tofu accounts for the least impacts in all the categories among all the meal options.

The climate change impacts for terrestrial and aquatic ecosystem have similar trajectory, while the results of land stress and water stress for the meals are alike with minor distinctions. The overall biodiversity impacts on both terrestrial and aquatic ecosystems are achieved by integrating the results from different impact categories for the corresponding ecosystem. The biodiversity impacts on terrestrial and aquatic ecosystem caused by the meals can be observed in Figure 7.

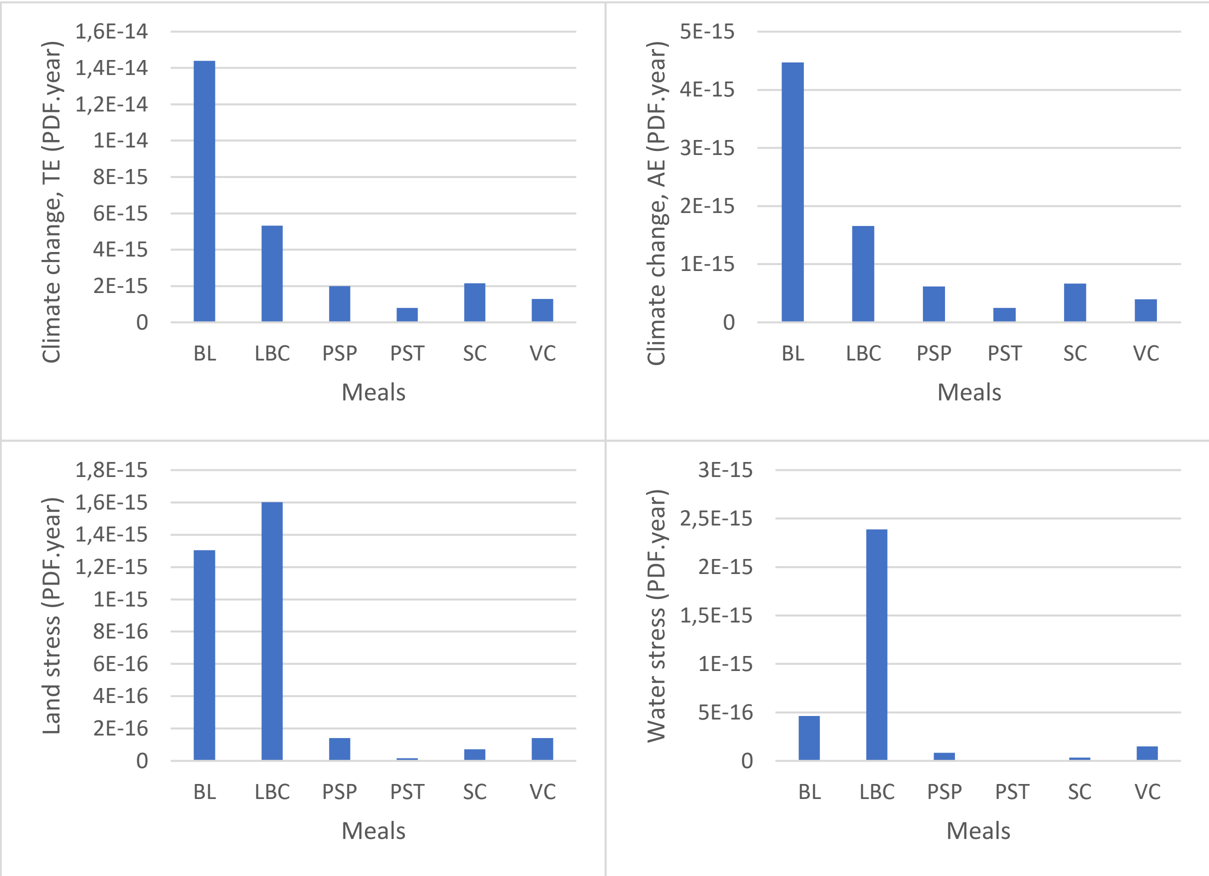

Figure 6. LCIA results of biodiversity impacts for the selected impact categories from the meals.

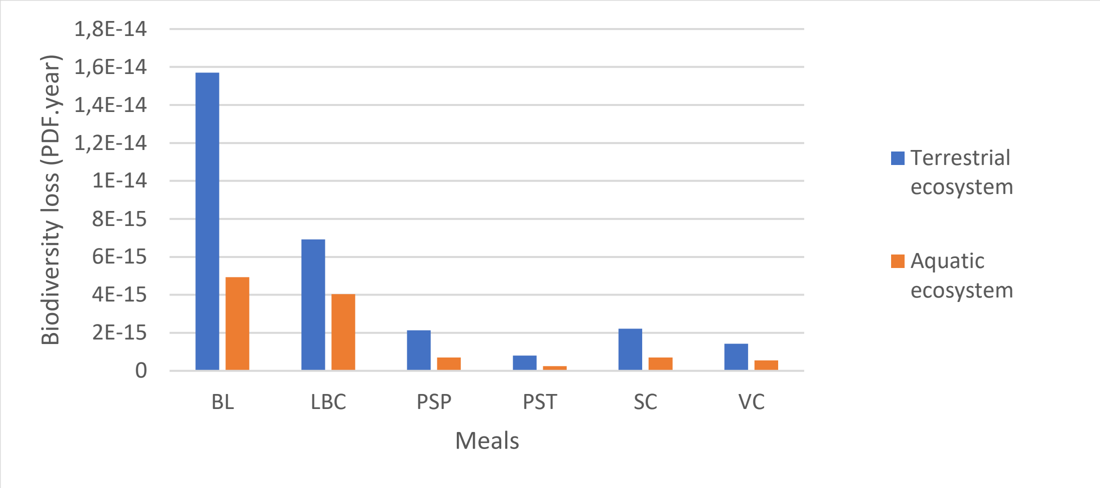

Figure 7. Biodiversity loss resulting from different meals for both terrestrial and aquatic ecosystems.

The results of Beef lasagne are considered as baseline with the objective of relative comparison of the results of the six meals. In comparison, Beef lasagne has 95% higher impacts for both terrestrial and aquatic ecosystems than the impacts from pea soup with tofu which is having the lowest impacts. Beef lasagne has 56% and 18% higher impacts for terrestrial and aquatic ecosystems respectively than lemon broiler chicken which is having the second highest impacts among the meal options. The higher impacts resulting from the meat-based meal options and beef resulting the highest overall impact is in line with the results from (Crenna, Sinkko and Sala, 2019; Mazac, Järviö and Tuomisto, 2023; Sanyé-Mengual *et al.*, 2023). Pea soup with pork and spinach crepes have almost identical results, nevertheless the impacts from spinach crepes exceeds the impacts from pea soup with pork by 4% for terrestrial and 2% for aquatic ecosystems respectively. Pea soup with tofu has the least overall impacts for both the ecosystems. Vegan casserole is the meal having the second least overall impact, and it has 43% and 54% higher impacts for terrestrial and aquatic ecosystems respectively in comparison with pea soup with tofu. On the whole, biodiversity impacts on terrestrial ecosystem is higher than that of the aquatic ecosystem for all the six meals.

Based on the overall biodiversity impacts on terrestrial ecosystems and aquatic ecosystems as shown in the Figure 7, the six different meals can be ranked according to their respective impacts on the biodiversity. All the six meals have similar linear progression in comparison with their impacts for terrestrial and aquatic ecosystems, and there is no major deviation. The ranking is provided in Table 12, and it is in the increasing order, i.e., the meal with the lowest overall impact for both the ecosystems scoring the rank 1, and the meal with highest impact scoring the rank 6. The interesting result from the ranking of meals is that of the spinach crepes and pea soup with pork, further analysis and reasoning for these results are provided in the subsequent sections.

Table 12. Ranking of meals based on overall biodiversity impacts.

Meal	Terrestrial ecosystem	Aquatic ecosystem	Ranking
Pea soup_Tofu	8,0677E-16	2,49305E-16	1
Vegan casserole	1,42482E-15	5,47204E-16	2
Pea soup_Pork	2,13247E-15	7,00489E-16	3
Spinach crepes	2,21616E-15	7,14405E-16	4
Lemon broiler chicken	6,92969E-15	4,04506E-15	5
Beef lasagne	1,56963E-14	4,93468E-15	6

5.2.1 Contribution analysis

To understand which ingredient was contributing the most to the biodiversity loss for different impact categories and to identify the hotspots in the ingredient's life cycle stages, a contribution analysis was carried out. The results are provided in the following section. In general, for all the ingredients, agriculture and its related activities were the biggest contributors to the overall impacts, it was nearly followed by the impacts from ingredient production stage. The contribution from the transportation and distribution, packaging, storage and meal preparation stages of the life cycle to the overall impacts were nominal. The water utilised during the meal preparation stages is not considered in the contribution analysis as the values were not obtained since it is considered as an elementary flow during the assessment stage. The contribution of ingredients for climate change endpoint category were identical for both terrestrial and aquatic ecosystems, hence the contributions for climate change is mentioned in the figures only once.

Minced beef accounted for the highest share of impacts for the beef lasagne in all the three impact categories, the share of minced beef in climate change impacts was 86.64%, and it had a share of 86.23% and 40.84% for land stress and water stress respectively. Figure 8 depicts the distribution of the share of impacts resulting from different ingredients used for beef lasagne. Contribution of the other ingredients are minimal for climate change and land stress, whereas for water stress other ingredients contribute to some extent. The higher share of impact of beef is attributed with the inventory flows associated with the feed used for cattle rearing, such as maize, wheat, soybean products, including grazing.

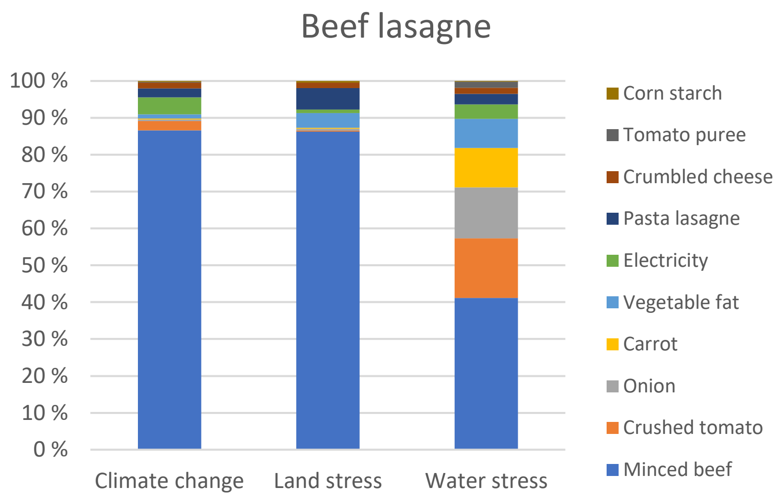

Figure 8. Contribution of ingredients to the biodiversity impact of beef lasagne.

It can be observed from Figure 9 that chicken meat accounts for more than 81% of the impacts from all the impact categories for lemon broiler chicken. Water stress has the highest impacts of 89.71%, these were mainly resulted during the stages of the chicken feed production and slaughtering and processing of the chicken. Feed production contributed approximately 46% and slaughtering and processing activities accounted for 41%. Furthermore, chicken feed production was the biggest contributor for land stress and climate change, accounting to almost 80% and 56% respectively. Contribution of the other ingredients to the impacts resulting from the meal is almost minimal.

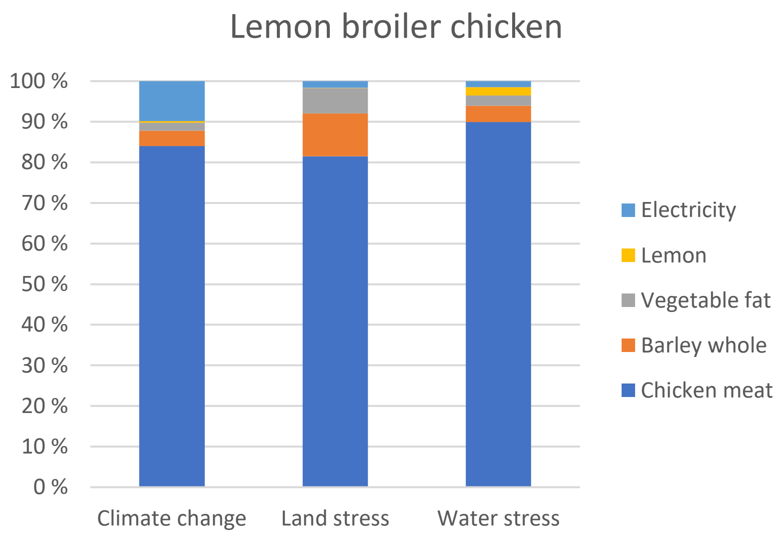

Figure 9. Contribution of ingredients to the biodiversity impact of lemon broiler chicken

The impact contribution from the ingredients in pea soup with pork varies as shown in the Figure 10. Pork is the highest contributor in climate change and water stress with 55.62 and 45.40% respectively, and dried split pea is the highest contributor for land stress with 56.07%. Electricity and onion also have notable contributions in different impact categories. The lower impacts of pork compared to other meat options such as beef and chicken is due to the lesser amounts of animal feed in the inventory flows. The inventory flows also include wheat straw, a by-product of wheat which is used as feed for the pork. However, the higher contributions towards water stress and climate change from pork is still the result of animal feed production, also due to processing and packaging of pork meat. Higher land stress impacts from the dried split pea are from the cultivation phase.

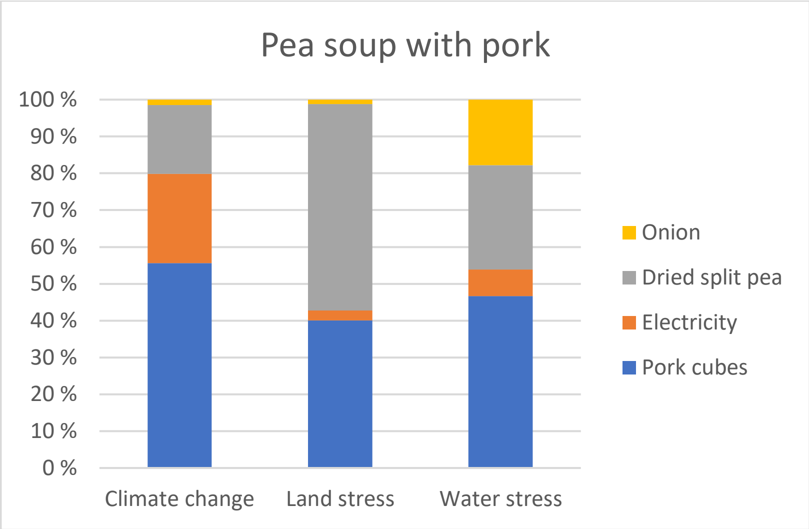

Figure 10. Contribution of ingredients to the biodiversity impact of pea soup with pork.

Pea soup with tofu has the least biodiversity impacts, and the distribution of the impacts from the ingredients is as shown in the Figure 11. Tofu comparatively has lesser impacts compared to other ingredients. Dried split pea is the significant contributor to the land stress and water stress categories. Whereas electricity consumption contributes most to the climate change. Significant impacts towards land stress and water stress from dried split pea is from the agricultural phase. The contribution of electricity towards climate change is attributed with the meal preparation phase.

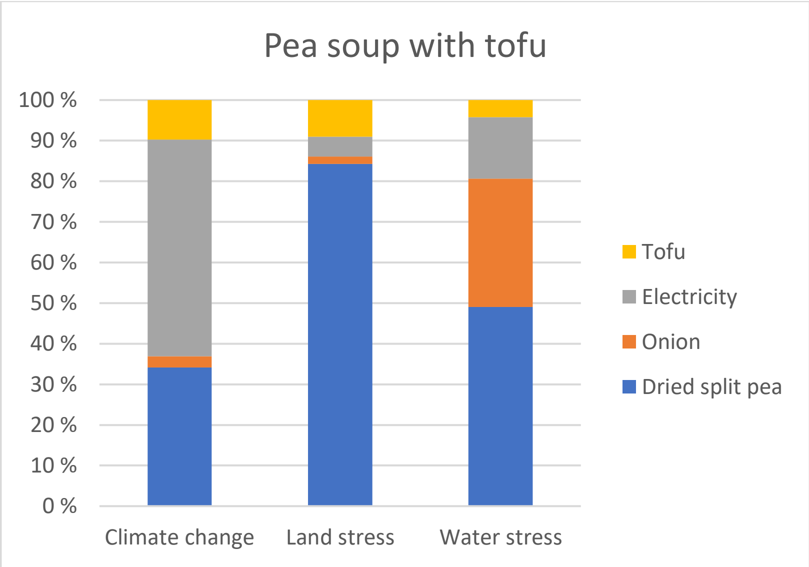

Figure 11. Contribution of ingredients to the biodiversity impact of pea soup with tofu.

The impacts from the spinach crepes are slightly higher than that of the pea soup with pork, the rationale behind these results can be analysed by the ingredients impact distribution provided in the Figure 12. The impacts slight proportionately distributed among the ingredients, but sour cream is the significant contributor to the impacts for all the three impact categories. The ingredients also involve, light fat milk and egg mass, which are animal-based products. The reasoning behind the high impacts from animal-based products are described in the above sections, which can be implemented to this case as well. This is also supported by the inventory flow data.

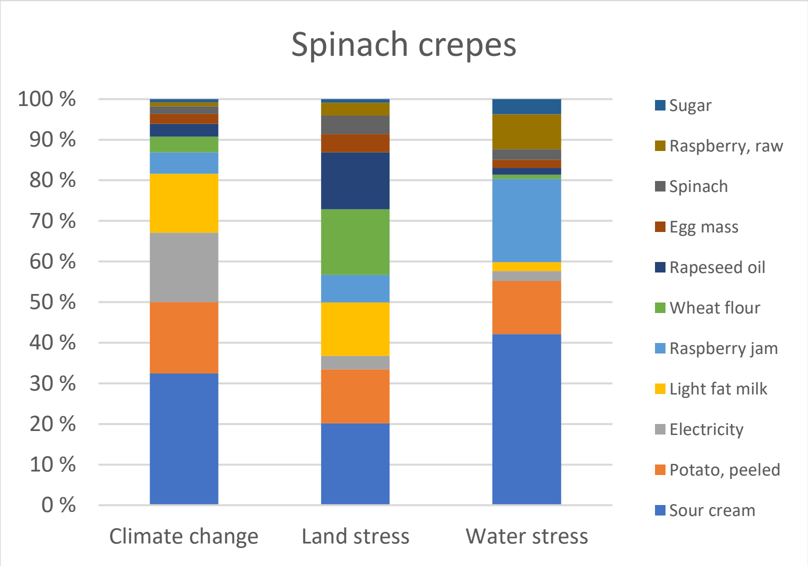

Figure 12. Contribution of ingredients to the biodiversity impact of spinach crepes.

Compared to other meals in this study, the share of the impacts from different ingredients for the vegan casserole is more evenly distributed among all the ingredients, the impacts of each ingredient are more notable and there no single ingredient dominating the impacts (Figure 13). However, electricity consumed while meal preparation is the major contributor towards climate change with 31.98%. Potato is the major contributor towards land use with 20.81% and closely followed by broad beans with 18.09%, the high impacts are during the agricultural phase which is driven by the use of fertilizers for both the ingredients. Peanut butter is the significant contributor with 40.01%, and this is due to the higher water consumption during agricultural irrigation.

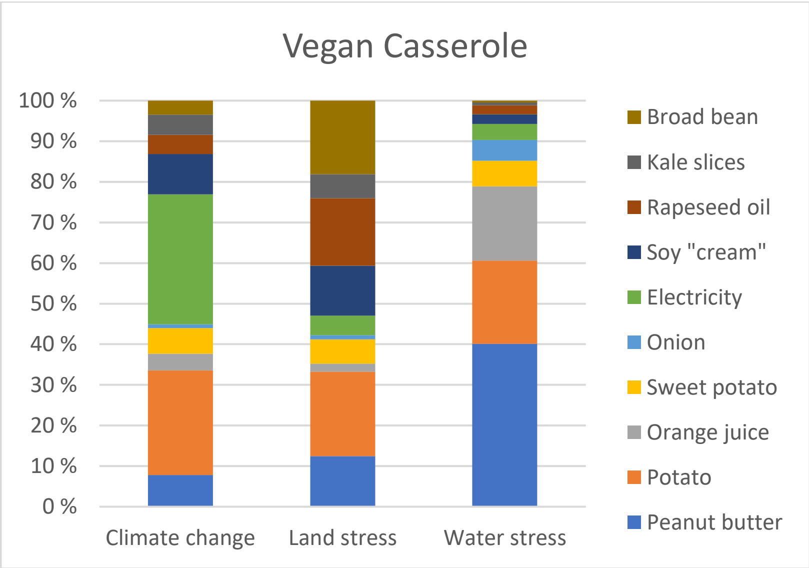

Figure 13. Contribution of ingredients to the biodiversity impact of vegan casserole.

5.2.2 Sensitivity analysis

The results of the sensitivity analysis are provided in this section. Sensitivity analysis was carried out to investigate the influence of the type and quantity of ingredients utilized in the recipes on biodiversity impacts from meals. However, sensitivity analysis was not conducted for the environmental impacts resulting from the meals, as the biodiversity impacts are the focus of this study.

Ingredients that were contributing the most in their respective meals, mainly meat options such as beef and chicken were replaced by other ingredients to assess the variations in the impacts. Changes in the location of origin was made to estimate the variation in impacts that can result from the utilization of regionalised characterization factors for land stress and water stress. Variations in the end impacts due to the consideration of flows was assessed by considering the impacts from total land use flows available from the inventory and comparing it with the impacts resulted from the flows that follow the cut off criteria of more than 1% contribution to the inventory results.

Replacements of key ingredients in two meals were made. Firstly, since beef lasagne had the highest biodiversity impacts among all the meals, the highest contributing ingredient beef was replaced by tofu, the key ingredient that was used in the meal that resulted in the least biodiversity impacts. Secondly, chicken was replaced with pork in the lemon broiler chicken, as the pea soup with pork had the least impact among all the meat-based meals.

Figure 14 shows the variation in the results of the meals resulted due to the change of ingredients. A remarkable reduction in the impacts of the meal can be seen by the replacement of beef using tofu, on the contrary, the impacts from the meal has increased after replacing chicken with pork. Impacts from beef lasagne was 89% higher than the impacts from tofu lasagne for both the ecosystems. For the comparison of the impacts for impact categories, water stress had the least change, as the impacts were higher by 24%, whereas climate change and land stress had higher impacts of 90% and 89% respectively from beef lasagne. Similarly, the lemon pork meal had 39% increase for climate change, 11% increase for land stress, and 28% increase for water stress compared to the impacts of lemon broiler chicken.

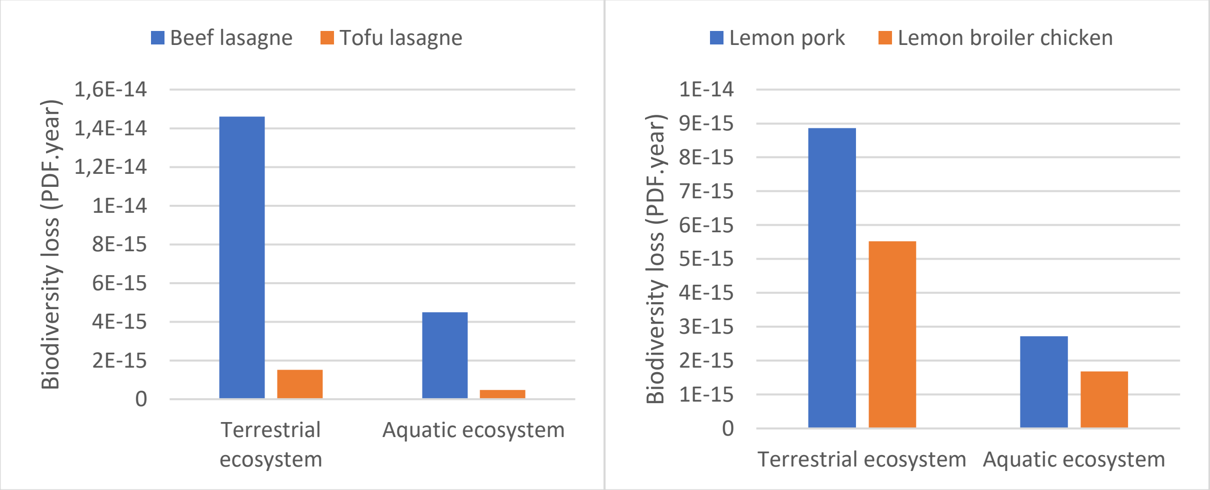

Figure 14. Variation in biodiversity impacts resulting from replacements of key ingredients.

To analyse the variation in results due to the use of regionalised characterization factors, the land stress and water stress impacts originating from Finland and France were compared (Figure 15). The global CFs were used for the ingredients assumed to be imported, and the regionalised CFs were used for the locally available ingredients. For the land stress comparison, three different types of meals were chosen, i.e., meat based, vegetarian, and vegan. Impacts from all the meals were used for comparison with regards to water stress.

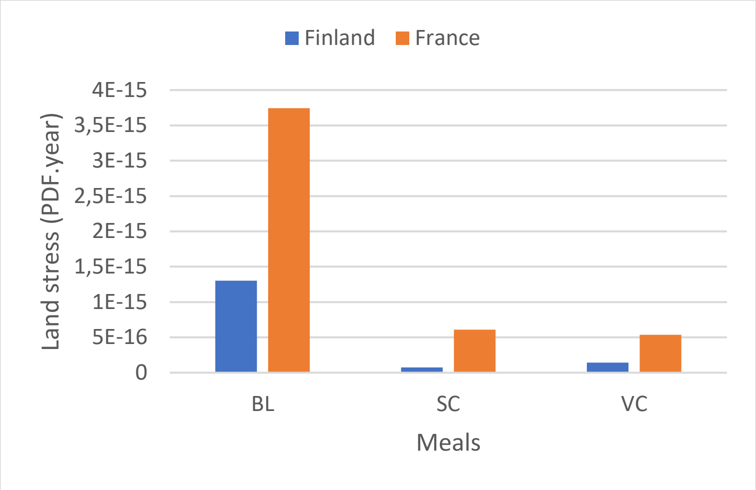

Figure 15. Comparison of regionalised land stress impacts.

The land stress impacts were considerably higher when the CFs belonging to France were used in comparison with Finland, which is shown in the Figure 15. Beef lasagne had 65.2%, spinach crepes had 88.1%, and vegan casserole had 73.7% increase in the land stress impacts respectively. However, while comparing the relative differences in the impacts, with the use of France CFs, spinach crepes had 48.5% higher impacts compared to vegan casserole, whereas vegan casserole had 12% higher impacts compared to spinach crepes while using CFs related to Finland.

The water stress impact comparison for the use of CFs from Finland and France are given in the Table 13. While land stress impacts were higher with the use of CFs from France in comparison with Finland, the water stress impacts are contrasting, as the impacts resulting from Finland CFs are higher than that of the France CFs. However, the variations in the impacts are not so notable with 5 out of 6 meals, the variations from pea soup with tofu stands out, as it has 21.7% higher impacts using Finland CF compared to France CF. This major variation can be attributed to the absence of global CFs in the meal impact calculations, as there are no imported ingredients used in pea soup with tofu.

Table 13. Comparison of regionalised water stress impacts.

Meals	Finland	France	% impact variation
BL	4,6141E-16	4,5855E-16	0.6 %
LBC	2,38908E-15	2,38586E-15	0.1 %
PSP	8,16445E-17	8,02296E-17	1.7 %
PST	3,45431E-18	2,70318E-18	21.7 %
SC	4,81619E-17	4,69413E-17	2.5 %
VC	1,48115E-16	1,47055E-16	0.7 %

To understand the role of contribution of the flows to the end impacts, comparison was made between the impacts resulting from the land use flows of beef lasagne (Figure 16). Impacts from the flows following the cut off criteria, i.e., the flows contributing more than 1% to the inventory were made with the impacts from the total inventory flows. Only the CFs from Finland were considered for this analysis, and the land stress impact while using total flows was 8.2% higher than the impacts resulting when using the flows that follow the cut off criteria.

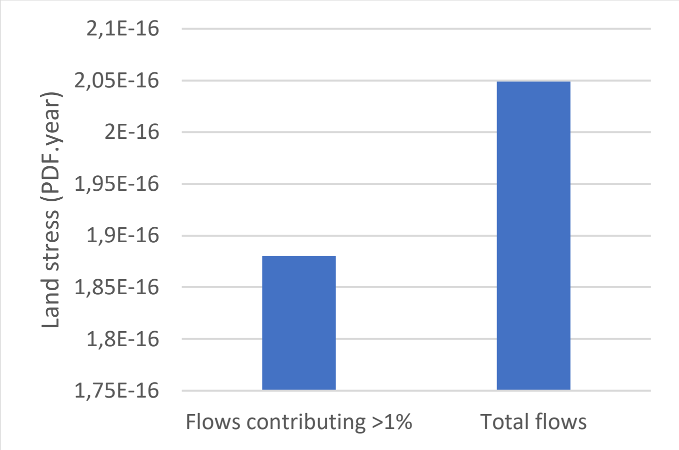

Figure 16. Variations in the end impacts due to different flow considerations for beef lasagna.

5.3 Discussion

It is evident from the results that the meat-based meals and the meals containing animal-based products result in higher biodiversity impacts compared to meal options that are comprised of plant-based ingredients. The higher impacts resulting from the animal-based products are mainly attributed to the animal feed used during the livestock production. Studies conducted by (Crenna, Sinkko and Sala, 2019; Sanyé-Mengual et al., 2023) also confirms the association of the high biodiversity impacts from animal-based products with the animal feed.

Based on the obtained results, meat-based meal options had the highest impacts in all the impact categories. On an average, vegetarian meal option results in lesser biodiversity impacts compared to meat-based meal options and more impacts compared to vegan and plant-based meat alternative, meal options. Vegan meal and plant-based meal options possess considerably lesser biodiversity impacts compared to meat-based meal options.

Pea soup with tofu had the least biodiversity impact among all the meal options in all the impact categories. However, in this study regarding pea soup with tofu, even though tofu is considered as an option to substitute meat, the meal recipe used in the study does not include any dairy products or eggs, hence it can also be considered as a vegan option. From the comparison of results from pea soup with tofu and the pea soup with pork, it is apparent that the plant-based meat alternative is clearly having lesser impacts than the meat option. (Mazac, Järviö and Tuomisto, 2023) in their study has considered meat imitates and tofu as different entities, and the results indicated that the meat imitates had a slightly higher environmental impacts than tofu. However, further analysis needs to be carried out using different plant-based meat substitute to have a better understanding of the biodiversity impact resulting from the consumption of plant-based meat alternatives, and its influence on the overall impacts of the meal.

The result of the biodiversity impacts, and environmental impacts from the study are identical. All the meals are ranked in the same order indicating the lowest and highest impacts in terms of the impacts caused for both the biodiversity and environmental impacts. Based on Table 11 and 12, it can be claimed that there are no major deviations in the correlation with the environmental impact and biodiversity impact results.

This LCA study shows that both type and quantity of the ingredients used for the meal preparation determines the magnitude of the overall biodiversity impacts caused by the meal. The primary reason is the significant and systematic variations in the biodiversity impacts originating from the different ingredients and their quantities used in meals. Meat products had the highest impacts in all impact categories, while the plant-based products had the least impacts.

Contribution analysis and sensitivity analysis shows that not only the type of the ingredient, but quantity of the ingredient used for the meal also plays a vital role, 60 grams of beef which accounts to 10.67% of weight of the ingredients, had influenced in higher overall impacts from the meal compared to 225 grams of chicken, 42.58% of the ingredient weight. Nevertheless, when the minced beef was replaced by tofu in the lasagne, the overall impacts from the meal was reduced by approximately 89% for both the ecosystems. Even though pea soup with pork, had lesser impacts than that of spinach crepes, the pork quantity in the meal contributed only for 5.91% of the overall ingredients. However, when chicken was replaced with same amount of pork in the meal, the overall biodiversity impacts from the meal increased, showing that the pork has relatively higher impacts than chicken when used in similar quantities. This implies that the beef has the highest impact among all the meat options, followed by pork and chicken respectively. The study conducted by (Crenna, Sinkko and Sala, 2019) indicates similar results, where beef meat, pork meat and poultry meat are the top three contributors among several food ingredients towards biodiversity loss.

Pork meat contributed more than 40% impacts in all the categories even though its contribution to the total weight of the ingredients was only 5.61%, whereas dried split pea’s share of weight among the ingredients was 19.34% and compared to pork it contributed less to climate change and water stress, and 16% more in land stress. Similar example is the contribution of higher impacts from sour cream compared to peeled potato in spinach crepes. Hence, it can be argued that the biodiversity impacts from plant-based ingredients are lesser than that of the animal derived products.

In comparison, climate change and land stress results from this study shows the land stress biodiversity impacts from all the meals were considerably lesser than that of the climate change impact results, whereas from the study conducted by (Crenna, Sinkko and Sala, 2019) in which the impacts are characterized using ReCiPe methods, the results for the climate change and land stress values were almost similar and there were even instances where land stress results for some ingredients exceeded the climate change results. Another study conducted by (Sanyé-Mengual *et al.*, 2023), where they compare the contribution of impact category groups to overall biodiversity impacts using various methods and models, land stress from LC-IMPACT accounted for only 1% of the contribution towards overall impact results, and climate change contributed 2.7%. For, ReCiPe climate change contribution was 43% and the land use contribution was 34% out of the overall biodiversity impacts. This difference in the contribution of different impact categories is mainly due to the non-homogenous coverage of impact categories across the LCIA methods and the difference in characterization factors associated with different LCIA methods. It is necessary to recognise that the various models are conceptually different for individual impact categories under a method’s framework. (Sanyé-Mengual *et al.*, 2023)

In LC-IMPACT there is a substantial difference between climate change and land use related biodiversity losses. The climate change impact model for biodiversity loss relies on climate change models, measuring average temperature increases and species loss over either a 100-year (core CFs) or 1000-year (extended CFs) time horizon. Meanwhile, land use-related biodiversity loss is calculated based on enhanced species-area relationships derived from empirical studies and data on endemic species richness to account for global species loss. Consequently, these impacts differ in terms of the time horizon covered and the timing of their effects (short-term for land use and longer-term for climate and toxicity). Such variations must be considered during interpretation of the results from impact assessment. For comparability, it is necessary to make normative choices rather than methodological modifications.(Sanyé-Mengual *et al.*, 2023)

From the results obtained from sensitivity analysis, it can be claimed that the locations from where the ingredients originate also plays a key role due to the use of regionalised CFs for the characterization of inventory results during impact assessment. The variation in the land stress and water stress impact results obtained by using different CFs for the assessment makes it apparent that the biodiversity impacts of the meals varies based on share of the imported ingredients included in the recipe.

The impact contribution among terrestrial ecoregions varies due to disparities in both the Life Cycle Inventory (LCI) and the Life Cycle Impact Assessment (LCIA) models, as the area used for cultivation and the harvested yield is different for different regions and crops. The CFs also differ across ecoregions, attributing to the variations in land use distribution, species richness, and the rarity and threat level of species. The above is also true for water consumption, in addition the results are driven by the variations in irrigation intensity and the CFs. (Verones *et al.*, 2020) This describes the variations in the results obtained from sensitivity analysis for land stress and water stress impacts.

5.4 Limitations and uncertainties

Although Life Cycle Assessment (LCA) is a widely accepted and valuable tool for evaluating the environmental impacts of products and services, it does have its constraints (Takacs *et al.*, 2022). Several assumptions are made in the framework of LCA regarding variables and scenarios, such aspects can impact the results and cause some uncertainties. Some of the limitations pertaining to the current study that can affect the end results are mentioned below.

Life cycle inventory assessment is one of the most crucial phases of any life cycle assessment (Takacs *et al.*, 2022). The background data related to production systems, transportation and other life stages were predominantly acquired from the Agribalyse database. The database version used for this study is v.3.0.1, which is an older version containing earlier datasets than the more recent version of the database, which may result in uncertainties with respect to data. Certain primary data such as electricity consumption during the meal preparation were acquired from literature, which was based on the assumption that similar appliances are used for meal preparation, which can be different in reality. Although some primary data was obtained from the recipes provided by the food service provider, the study still lacked in terms of primary data, which might have somewhat altered the outcome of the assessment.

The study is based in Finland, hence the country specific inventory data related to the ingredients originating from Finland were sourced for whichever available. For the other ingredients that are considered to be imported, for ease of calculation, it was assumed to be of global origin and not country specific, which can induce some deviations in the actual results if country specific origin of the ingredients were considered.

The selected system boundary, functional unit, impact categories, LCIA methods and models, value choices and other methodological choices could significantly alter the end results and might affect the comprehensiveness of the overall study. The study was limited to three endpoint impact categories to assess the biodiversity impacts of the meals, while they provide satisfactory synopsis of the significant biodiversity impacts associated with the meals, including the other impact categories related to the food sector such as terrestrial acidification, freshwater eutrophication, and others will assist to achieve comprehensive understanding of the biodiversity impacts from the meals. The same applies for the midpoint impact categories used to assess environmental impacts.

The functional unit used for this study is single serving portion of the meal, which is a mass based functional unit. Even though it makes it easier to understand and interpret the results, consideration of nutritional quality of the meal and ingredients can provide more extensive results related to biodiversity impacts.

Since, the LC-IMPACT method is not available readily on openLCA software, the impact assessment involved manual calculations using MS-Excel. In this situation, potential human error during the calculations cannot be ignored, such calculation errors might produce results which are unreliable. Availability of the LCI databases and LCIA models in the LCA software allows easy characterization of the inventory flows, however, manual mapping of the flows is challenging due to difference between the LCI nomenclature and LCIA method which can cause inconsistencies in the end results (Sanyé-Mengual *et al.*, 2022).

Although numerous LCA studies exist that evaluate and compare the environmental impacts of various food options, the same level of attention and research has not been observed in the context of biodiversity impacts. Even the existing studies (Crenna, Sinkko and Sala, 2019; Sanyé-Mengual *et al.*, 2022) uses global average CFs for assessment and does not accommodate assessments using regionalised characterization factors, which makes it difficult to compare the results from the study to similar literature.

5.5 Recommendations

Good quality data is a crucial part of any LCA study, inclusive dataset emanates a comprehensive LCA study and provides robust and reliable results (Sanyé-Mengual et al., 2023). Hence, further assessment with a more inclusive dataset shall be carried out. Country specific data collection is required to characterize inventory flows with country specific CFs for the ingredients originating from that country in order to obtain more accurate impacts on biodiversity.

Specifically, to adequately account for technology advancements (e.g., agricultural yields), LCI data should accurately reflect the relevant time period. Emphasis should be placed on acquiring high-quality data concerning crop yield, as it directly influences the related land impacts.(Sanyé-Mengual *et al.*, 2023)

The functional unit can be altered to compare different quantities of the ingredients and to incorporate nutritional values of the meals in the study, in order to facilitate decision making. System boundary can be expanded to assess the biodiversity impacts included during and after the human consumption of the meals, as resources and energy are consumed during this phase (Notarnicola *et al.*, 2017). The functional unit used in this study is of the single serving portion of the meal, however the serving portion quantity varies for the different meals. Hence, assessment with a functional unit having similar quantities may offer better comparison of the impacts from ingredients. In order to avoid any errors during biodiversity impact calculations and to achieve more detailed results, utilization of LCA software accommodating the appropriate LCI database and LCIA method is necessary.

LC-IMPACT is still in its initial stages of development and do lack in terms of coverage of impact pathways, and level of detail within impact categories. Further research is required to obtain more comprehensive results by including impacts on ecosystems from aspects such as noise, invasive species, salinization, ocean acidification and others. (Verones *et al.*, 2020)

Further research is required in the field to assess the biodiversity impacts resulting from food products from an expanded basket of products. It is recommended to employ the latest, state-of-the-art methods in order to handle uncertainties in the assessment more effectively (Crenna, Sinkko and Sala, 2019). Further studies should integrate the dynamics of different production systems, to achieve a comprehensive understanding of the interplay between different meal options and their biodiversity impacts. Contributions should be made towards harmonizing the LCI nomenclatures in accordance with LCIA methods and LCA software's for a homogenous approach towards LCA of biodiversity impacts (Sanyé-Mengual *et al.*, 2022).

6 Conclusion

The primary objective of this study was to assess the biodiversity impacts resulting from six different meals, belonging to different meal categories such as meat based, vegetarian, vegan and plant-based meat alternative meals. The assessment was conducted to assist the decision making of the food service provider and the consumers, to choose the meal for consumption based on the biodiversity impacts of the meal options. Based on the results obtained from the study, it was the type and quantity of the ingredients used in the meals which determined the magnitude of the outcome of the meals in terms of biodiversity impacts. The results and the rankings given for the meals based on their impacts explicitly showed that the biodiversity impacts resulting from the meals that were plant based had significantly lower impacts than the meals containing meat and other animal-based products. The end results for the midpoint and endpoint categories for environmental impacts and biodiversity impacts suggest identical outcomes from the study.

It was noticed that the impact contribution from the different meat options were the highest contributor in the overall impacts, meat options contributed more even when the weight share of the meat among the ingredients was lesser than other ingredients. Substantial reductions in the biodiversity impacts were observed when the ingredient that has the highest impacts, i.e., beef was replaced with the tofu which is a plant-based ingredient. Almost, 89% reduction in the overall impacts from the meal was observed due to this replacement. Further, with the use of regionalised characterization factors for the impact assessment, it was also noticed that the origin of the ingredient also plays a key role in the assessment of biodiversity impacts caused from the meal options. The impacts from the ingredients that were imported, possessed relatively higher overall impacts compared to the ingredients originating from Finland. However, (Crenna, Sinkko and Sala, 2019) and (Takacs et al., 2022) mentioned in their studies that the respective biodiversity impacts, and the environmental impacts were considerably higher than the locally sourced meat-based ingredients. But the ecoregion in which the ingredients are cultivated, can influence in the variation in the impacts.

From the analysis of the life cycle stages of the ingredients that are major contributors to the biodiversity impact, it was noted that the agricultural activities and ingredient production phases had the biggest contribution towards biodiversity impacts from the meals. Other life cycle stages contributed towards the biodiversity impacts, but the extent of the impacts was relatively smaller.

Food service provider and consumers can take into consideration the findings of the study in their decision making. Food service provider can opt and source the ingredients that are having relatively lower biodiversity impacts and exclude the ingredients that result in increased impacts. Since, the meat-based meals induce the highest biodiversity impacts, food service provider can gradually move away from the usage of meat-based ingredients in their food meal. Replacing the meat with available plant-based meat substitutes can be an effective strategy to achieve reductions in the biodiversity impacts resulting from meals. The dairy products can also be replaced with suitable plant-based alternatives.

If immediately moving away from the meat-based meals are not an option, then the food service provider can opt for the comparatively lesser impacting meat option and use it less, in this case it is chicken when all the meat is assessed for the same proportion. Another option is to choose for the meat-based meal where the least amount of meat is used, which in turn result in relatively lesser biodiversity impacts, in this instance it is pea soup with pork. However, the best option to substantially reduce the overall biodiversity impacts from the meal options is to scantily use or not use any animal derived ingredients in the meals.

Based on the results provided from the study, the consumers can opt for the meal options that are having lesser impacts on the biodiversity, i.e., plant-based meal options. In case, consuming meat is a must, then they can opt for the meal option with meat which is contributing the least among meat option towards biodiversity impacts. This study shows that replacing meat, dairy and other animal-based product with plant-based products results in lesser overall biodiversity impacts and assists in safeguarding the biodiversity.

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Appendices

Appendix 1. Ingredient composition of Beef lasagne.

Ingredients	Quantity in g	Share by weight (in %)
Minced beef browned	60	10.67
Carrot stick	27.5	4.89
Onion cube	30	5.33
Water	227.5	40.44
Crushed tomato	100	17.78
Tomato puree	12.5	2.22
Vegetable fat blend 15%	20	3.56
Corn starch	8	1.42
Pasta lasagne	57.5	10.22
Crumbled cheese	10	1.78

Appendix 2. Ingredient composition of Lemon broiler chicken.

Ingredients	Quantity in g	Share by weight (in %)
Barley whole	65	12.30
Water	202.27	38.28
Vegetable fat blend 15%	15.4	2.91
Lemon	5.92	1.12
Chicken meat - unseasoned	225	42.58

Appendix 3. Ingredient composition of Pea soup – Pork.

Ingredients	Quantity in g	Share by weight (in %)
Dried split pea	98.2	19.34
Water	357.14	70.34
Onion cubes	15.8	3.11
Pork cubes	30	5.91

Appendix 4. Ingredient composition of Pea soup – Tofu.

Ingredients	Quantity in g	Share by weight (in %)
Dried split pea	72.3	17.64
Water	290	70.77
Onion cube	11.9	2.90
Tofu cubes	30	7.32

Appendix 5. Ingredient composition of Spinach Crepes .

Ingredients	Quantity in g	Share by weight (in %)
Egg mass	6.7	1.56
Light fat milk	63.75	14.82
Wheat flour	31.02	7.21
Sugar crystal	7	1.63
Spinach chopped	37.5	8.72
Rapeseed oil	10.02	2.33
Peeled potato	180	41.85
Sour cream	57.75	13.43
Raspberry jam	20	4.65
Raspberry, raw	7	1.63

Appendix 6. Ingredient composition of Vegan Casserole.

Ingredients	Quantity in g	Share by weight (in %)
Potato washed	195.31	46.48
Rapeseed oil	8,9	2.12
Onion peeled	8	1.90
Sweet potato peeled	60	14.28
Kale slices	17.5	4.16
Broad bean	30	7.14
Water	45	10.71
Concentrated orange juice	15	3.57
Peanut butter	9	2.14
Soy "cream"	25	5.95

Appendix 7. Life Cycle results for Beef Lasagna (FU – 1 serving portion)

Inputs	**Flow**	**Unit**	**Result**
Resource	Carbon dioxide, in air	kg	5,041289
	Land Occupation	m^2*a	4,74809
	Land Transformation (from)	m^2	0,480558
	Land Transformation (to)	m^2	0,480419
	Water	m^3	0,017349
Output	**Flow**	**Unit**	**Result**
Emission to air	Carbon dioxide	kg	0,669441
	Methane	kg	0,070612
	Dinitrogen monoxide	kg	0,001827

	Sulfur hexafluoride	kg	1,28E-07
Emission to soil	Carbon dioxide, to soil or biomass stock	kg	3,46E-06

Appendix 8. Life Cycle Inventory for Lemon Broiler Chicken (FU – 1 serving portion).

Inputs	**Flow**	**Unit**	**Result**
Resource	Carbon dioxide, in air	kg	2.77624E-15
	Land Occupation	m^2*a	1.659286048
	Land Transformation (from)	m^2	0.914841748
	Land Transformation (to)	m^2	0.914842668
	Water	m^3	0.030828409
Output	**Flow**	**Unit**	**Result**
Emission to air	Carbon dioxide	kg	1.0401192
	Methane	kg	0.004237191
	Dinitrogen monoxide	kg	0.001054284
	Sulfur hexafluoride	kg	1.04717E-07
	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	3.58002E-06
Emission to soil	Carbon dioxide, to soil or biomass stock	kg	3.19255E-06

Appendix 9. Life Cycle Inventory for Pea Soup - Tofu (FU – 1 serving portion)

Inputs	**Flow**	**Unit**	**Result**
Resource	Carbon dioxide, in air	kg	4.3955E-16
	Land Occupation	m^2*a	0.450414875
	Land Transformation (from)	m^2	0.033952763
	Land Transformation (to)	m^2	0.033952777
	Water	m^3	0.003844106
Output	**Flow**	**Unit**	**Result**
Emission to air	Carbon dioxide	kg	0.164664009
	Methane	kg	0.000633775
	Dinitrogen monoxide	kg	5.53974E-05
	Sulfur hexafluoride	kg	5.72211E-08
	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	3.66383E-07
Emission to soil	Carbon dioxide, to soil or biomass stock	kg	2.11203E-07

Appendix 10. Life Cycle Inventory for Pea Soup - Pork (FU – 1 serving portion).

Inputs	**Flow**	**Unit**	**Result**
Resource	Carbon dioxide, in air	kg	1.15499E-15
	Land Occupation	m^2*a	0.908681514
	Land Transformation (from)	m^2	0.050492183
	Land Transformation (to)	m^2	0.050492378
	Water	m^3	0.00769591
Output	**Flow**	**Unit**	**Result**

Emission to air	Carbon dioxide	kg	0.281868918
	Methane	kg	0.004499001
	Dinitrogen monoxide	kg	0.000240274
	Sulfur hexafluoride	kg	7.94103E-08
	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	4.92506E-08
Emission to soil	Carbon dioxide, to soil or biomass stock	kg	7.86705E-07

Appendix 11. Life Cycle Inventory for Spinach Crepes (FU – 1 serving portion).

Inputs	**Flow**	**Unit**	**Result**
Resource	Carbon dioxide, in air	kg	1.06775E-15
	Land Occupation	m^2*a	0.684110894
	Land Transformation (from)	m^2	0.291896495
	Land Transformation (to)	m^2	0.291896569
	Water	m^3	4.14616E-18
Output	**Flow**	**Unit**	**Result**
Emission to air	Carbon dioxide	kg	0.413773068
	Methane	kg	0.004109201
	Dinitrogen monoxide	kg	0.000281813
	Sulfur hexafluoride	kg	7.64625E-08
	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	3.40933E-06
	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	4.26106E-08
Emission to soil	Carbon dioxide, to soil or biomass stock	kg	7.60544E-05

Appendix 12. Life Cycle Inventory for Vegan Casserole (FU – 1 serving portion).

Inputs	**Flow**	**Unit**	**Result**
Resource	Carbon dioxide, in air	kg	6.42352E-16
	Land Occupation	m^2*a	0.526639221
	Land Transformation (from)	m^2	0.278149977
	Land Transformation (to)	m^2	0.278149995
	Water	m^3	0.006292226
Output	**Flow**	**Unit**	**Result**
Emission to air	Carbon dioxide	kg	0.294584598
	Methane	kg	0.000754788
	Dinitrogen monoxide	kg	0.000161158
	Sulfur hexafluoride	kg	7.44499E-08
	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	kg	3.70362E-06
	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	kg	4.26747E-08
Emission to soil	Carbon dioxide, to soil or biomass stock	kg	0.001365661

Appendix 13. Biodiversity LCIA results for different impact categories.

Results	**Climate Change, TE**	**Climate Change, AE**	**Land stress**	**Water Stress**
Beef lasagne	1,43924E-14	4,47327E-15	1,30387E-15	4,6141E-16
Lemon broiler chicken	5,32834E-15	1,65598E-15	1,60135E-15	2,38908E-15
Pea soup_Pork	1,99115E-15	6,18845E-16	1,41313E-16	8,16445E-17
Pea soup_Tofu	7,91041E-16	2,45851E-16	1,57289E-17	3,45431E-18
Spinach crepes	2,14367E-15	6,66243E-16	7,24857E-17	4,81619E-17
Vegan casserole	1,28411E-15	3,99089E-16	1,40704E-16	1,48115E-16

Appendix 14. Environmental LCIA results for different impact categories.

Results	**Climate change (kg CO_2 eq)**	**Land use (m^2a crop eq)**	**Water consumption (m^3)**	**Freshwater eutrophication (kg P eq)**
Beef lasagne	3.62924414	3.314961824	0.03551	0.000303
Lemon broiler chicken	1.51561209	1.660028098	0.057668	0.000374
Pea soup_Pork	0.5115006	0.817265807	0.015691	0.00015
Pea soup_Tofu	0.2062351	0.40037257	0.007961	8.2E-05
Spinach crepes	0.65135176	0.610277118	0.01943	0.000137
Vegan casserole	0.38120224	0.456320967	0.017692	0.000106

Appendix 15. Electricity consumption data for meal preparation.

Type of cooking	**Quantity of food**	**Electricity used**	**Data source**
Oven baking	1000 g	1.35 kWh	Agribalyse v.3.0.1
Stove top cooking	800 g	0.89 kWh	(Calderón *et al.*, 2010)

Appendix 16. Food crops considered to be originating from Finland and their yields (2022).

Food crops	**Yield**	**Unit**
Carrot	47830	kg/Ha
Onion	23531	kg/Ha
Tomato	139860	kg/1000 m^2
Wheat	3850	kg/Ha
Barley	2.58	m^2/kg
Pea	2920	kg/Ha
Fava bean	4.88	m^2/kg
Spinach	0.648	m^2/kg
Potato	29040	kg/Ha
Raspberry	2.318	m^2/kg
Cauliflower* (used for kale)	9191	kg/Ha

Appendix 17. Portion of the ingredients considered to be imported.

Meals	**Imported share of ingredients (in %)**
Beef lasagne	15.64%
Lemon broiler chicken	46.62%
Pea soup_Pork	5.91%
Pea soup_Tofu	0%
Spinach crepes	3.96%
Vegan casserole	13.78%