1st Draft Product Environmental Footprint of the Representative Product for Vegetables

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Disclaimer

This it is not a stand-alone document but should be read in parallel to the report 'Product Environmental Footprint Category Rules for Fruits and Vegetables, 1st Draft, Wageningen, Report 2024-049, Wageningen Economic Research (Weststrate et al., 2024). The purpose of this representative product study was to identify the most relevant impact categories, life cycle stages, processes and (direct) elementary flows and also to identify the data needs, all feeding into the methodology development for FreshProducePEFCR. The study is as much as possible conducted according to the most recent version of the Product Environmental Footprint Guidance – PEF Guidance (EC, 2021).

Key words: life cycle assessment, PEFCR, vegetables, environmental impact, fresh produce

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Preface

This document is offered to professionals who would like to learn more about the state of the art regarding the environmental footprint of fresh vegetables. The document has been prepared by a group of international experts who also delivered similar work for the sector of floriculture. The development of a (shadow) PEFCR for the fresh fruit and vegetable sector – FreshProducePEFCR – ran from January 2023 and is expected to be finished in the first quarter of 2025. The work is carried out by an international consortium of partners (the Technical Secretariat) led by Freshfel Europe. The development of the methodology followed as much as possible the most recent Guidance for developing Product Environmental Footprint Category Rules (PEFCR) published by the European Commission in 2021.

This technical document – Product Environmental Footprint Representative Product (PEF-RP) for vegetables – is prepared with the following aims:

1. Identifying the most relevant impact categories;
2. Identifying the most relevant life cycle stages, processes and elementary flows;
3. Identifying data needs, data collection activities and data quality requirements.

This PEF-RP report follows the PEF-study template as provided in Annex E of the PEFCR Guideline and includes the characterised, normalised and weighted results. Some of the data used in this study are from primary sources and remain confidential.

Developing a PEFCR for the fresh fruit and vegetable sector was a process spanning several years that required intensive engagement of different stakeholders and substantial resources. However, collective sector efforts will see the wider sector benefit from this FreshProducePEFCR and succeed in reducing the environmental impact of fresh produce. The development and application of the PEF method is complex. The FreshProducePEFCR will derive 16 important environmental indicators in total, among which are included climate change, resource use (fossils), toxicity, acidification, water use, and land use. The large number of indicators and the complex method result in heavy data demand on primary processes in the fresh fruit and vegetable sector, i.e. on everything that a farmer decides upon. Some of the life cycle stages are modelled based on company-specific data because these have a large influence on the total impact on a product. Other stages are modelled using default data provided by the FreshProducePEFCR itself through rules and databases.

We especially would like to thank the organisations for providing company-specific data and for reflecting on the results of the representative product studies that have been contributing to the methodology development. A special thanks goes to all the members of Freshfel Europe's Environmental Footprint Initiative for their valuable support and feedback during the process and studies.

This document is not stand-alone and should be read in parallel to the report 'Product Environmental Footprint Category Rules for Fruits and Vegetables' This 1st Draft is released for the 1st Open Public Consultation through which feedback is requested. The comments will be addressed in the next round of revisions and thereby continuous development and improvement of this document will take place until its final release, expected early 2025.

Managing Director Social Sciences Group (SSG)
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Chair of the Technical Secretariat of the FreshProducePEFCR
Freshfel Europe

Acronyms

BSI	British Standards Institution
CF	characterization factor
CFF	Circular Footprint Formula
CPA	Classification of Products by Activity
DC	distribution centre
dLUC	Direct Land Use Change
DQR	Data Quality Rating
EC	European Commission
EF	environmental footprint
EoL	end of life
FU	functional unit
GHG	greenhouse gas
GWP	global warming potential
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
JRC	Joint Research Centre
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LU	Land Use
PEF	product environmental footprint
PEFCR	product environmental footprint category rules
PEF-RP	PEF study of the representative product
PY	person-year
RP	representative product
TS	Technical Secretariat

Definitions

Activity data - information which is associated with processes while modelling Life Cycle Inventories (LCI). The aggregated LCI results of the process chains, which represent the activities of a process, are each multiplied by the corresponding activity data[1] and then combined to derive the environmental footprint associated with that process.

Examples of activity data include quantity of kilowatt-hours of electricity used, quantity of fuel used, output of a process (e.g. waste), number of hours equipment is operated, distance travelled, floor area of a building, etc.

Synonym of 'non-elementary flow'.

Acidification – Environmental Footprint (EF) impact category that addresses impacts due to acidifying substances in the environment. Emissions of NO_x, NH_3 and SO_x lead to releases of hydrogen ions (H+) when the gases are mineralised. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lake acidification.

Additional environmental information – environmental information outside the EF impact categories that is calculated and communicated alongside PEF results.

Aggregated dataset - complete or partial life cycle of a product system that – next to the elementary flows (and possibly not relevant amounts of waste flows and radioactive wastes) – itemises only the product(s) of the process as reference flow(s) in the input/output list, but no other goods or services.

Aggregated datasets are also called 'LCI results' datasets. The aggregated dataset may have been aggregated horizontally and/or vertically.

Allocation – an approach to solving multi-functionality problems. It refers to 'partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems'.

Background processes – refers to those processes in the product life cycle for which no direct access to information is possible. For example, most of the upstream life-cycle processes and generally all processes further downstream will be considered part of the background processes.

Benchmark – a standard or point of reference against which any comparison may be made. In the context of PEF, the term 'benchmark' refers to the average environmental performance of the representative product sold in the EU market.

Characterisation – calculation of the magnitude of the contribution of each classified input/output to their respective EF impact categories, and aggregation of contributions within each category.

This requires a linear multiplication of the inventory data with characterisation factors for each substance and EF impact category of concern. For example, with respect to the EF impact category 'climate change', the reference substance is CO_2 and the reference unit is kg CO_2-equivalents.

Characterisation factor (CF) – factor derived from a characterisation model which is applied to convert an assigned life cycle inventory result to the common unit of the EF impact category indicator.

[1] Based on GHG protocol scope 3 definition from the Corporate Accounting and Reporting Standard (World resources institute, 2011)

Climate change – EF impact category considering all inputs and outputs that result in greenhouse gas (GHG) emissions. The consequences include increased average global temperatures and sudden regional climatic changes.

Company-specific data – refers to directly measured or collected data from one or more facilities (site-specific data) that are representative for the activities of the company (company is used as synonym of organisation). It is synonymous to 'primary data'. To determine the level of representativeness a sampling procedure may be applied.

Comparison – a comparison, not including a comparative assertion, (graphic or otherwise) of two or more products based on the results of a PEF study and supporting PEFCRs.

Consumer – an individual member of the general public purchasing or using goods, property or services for private purposes.

Co-product – any of two or more products resulting from the same unit process or product system.

Cradle to grave – a product's life cycle that includes raw material extraction, processing, distribution, storage, use, and disposal or recycling stages. All relevant inputs and outputs are considered for all of the stages of the life cycle.

Data quality – characteristics of data that relate to their ability to satisfy stated requirements. Data quality covers various aspects, such as technological, geographical and time-related representativeness, as well as completeness and precision of the inventory data.

Data quality rating (DQR) - semi-quantitative assessment of the quality criteria of a dataset, based on technological representativeness, geographical representativeness, time-related representativeness, and precision. The data quality shall be considered as the quality of the dataset as documented.

Delayed emissions – emissions that are released over time, e.g. through long use or final disposal stages, versus a single emission at time t.

Direct elementary flows (also named elementary flows) – all output emissions and input resource uses that arise directly in the context of a process. Examples are emissions from a chemical process, or fugitive emissions from a boiler directly onsite.

Direct land use change (dLUC) – the transformation from one land use type into another, which takes place in a unique land area and does not lead to a change in another system.

Downstream – occurring along a product supply chain after the point of referral.

Ecotoxicity, freshwater – EF impact category that addresses the toxic impacts on an ecosystem, which damage individual species and change the structure and function of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem.

Elementary flows – in the life cycle inventory, elementary flows include 'material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation'.

Elementary flows include, for example, resources taken from nature or emissions into air, water, soil that are directly linked to the characterisation factors of the EF impact categories.

Environmental footprint (EF) impact assessment – phase of the PEF analysis aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product. The impact assessment methods provide impact characterisation factors for elementary flows, to aggregate the impact so as to obtain a limited number of midpoint indicators.

Environmental footprint (EF) impact assessment method – protocol for converting life cycle inventory data into quantitative contributions to an environmental impact of concern.

Environmental footprint (EF) impact category – class of resource use or environmental impact to which the life cycle inventory data are related.

Environmental footprint (EF) impact category indicator – quantifiable representation of an EF impact category. Environmental impact – any change to the environment, whether adverse or beneficial, that wholly or partially results from an organisation's activities, products or services.

Eutrophication – EF impact category related to nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilised farmland that accelerate the growth of algae and other vegetation in water. The degradation of organic material consumes oxygen, resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of substances emitted into a common measure, expressed as the oxygen required for the degradation of dead biomass. To assess the impacts due to eutrophication, three EF impact categories are used: eutrophication, terrestrial; eutrophication, freshwater; eutrophication, marine.

Flow diagram – schematic representation of the flows occurring during one or more process stages within the life cycle of the product being assessed.

Functional unit (FU) – defines the qualitative and quantitative aspects of the function(s) and/or service(s) provided by the product being evaluated. The functional unit definition answers the questions 'what?', 'how much?', 'how well?', and 'for how long?'.

Global warming potential (GWP) – An index measuring the radiative forcing of a unit mass of a given substance accumulated over a chosen time horizon. It is expressed in terms of a reference substance (for example, CO_2- equivalent units) and specified time horizon (e.g. GWP 20, GWP 100, GWP 500 – for 20, 100 and 500 years, respectively).

By combining information on both radiative forcing (the energy flux caused by emission of the substance) and on the time it remains in the atmosphere, GWP gives a measure of a substance's capacity to influence the global average surface-air temperature and therefore subsequently influence various climate parameters and their effects, such as storm frequency and intensity, rainfall intensity and frequency of flooding, etc.

Human toxicity – cancer – EF impact category that accounts for adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin – insofar as they are related to cancer.

Human toxicity - non cancer – EF impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin – insofar as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.

Ionising radiation, human health – EF impact category that accounts for the adverse health effects on human health caused by radioactive releases.

Land use (LU) – EF impact category related to use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, mining, etc.

Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in soil quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in soil quality multiplied by the area).

Life cycle – consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life cycle assessment (LCA) – compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life cycle impact assessment (LCIA) – phase of life cycle assessment that aims to understand and evaluate the magnitude and significance of the potential environmental impacts for a system throughout the life cycle.

The LCIA methods used provide impact characterisation factors for elementary flows to aggregate the impact, to obtain a limited number of midpoint and/or damage indicators.

Life cycle inventory (LCI) - the combined set of exchanges of elementary, waste and product flows in a LCI dataset.

Multi-functionality – if a process or facility provides more than one function, i.e. it delivers several goods and/or services (‘co-products’), then it is ‘multifunctional‘. In these situations, all inputs and emissions linked to the process will be partitioned between the product of interest and the other co-products, according to clearly stated procedures.

Normalisation – after the characterisation step, normalisation is the step in which the life cycle impact assessment results are divided by normalisation factors that represent the overall inventory of a reference unit (e.g. a whole country or an average citizen).

Normalised life cycle impact assessment results express the relative shares of the impacts of the analysed system, in terms of the total contributions to each impact category per reference unit.

Displaying the normalised life cycle impact assessment results for the different impact topics next to each other shows which impact categories are affected most and least by the analysed system.

Normalised life cycle impact assessment results reflect only the contribution of the analysed system to the total impact potential, not the severity/relevance of the respective total impact. Normalised results are dimensionless, but not additive.

Ozone depletion – EF impact category that accounts for the degradation of stratospheric ozone due to emissions of ozone-depleting substances, for example long-lived chlorine and bromine containing gases (e.g. chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons).

Particulate matter – EF impact category that accounts for the adverse effects on human health caused by emissions of particulate matter (PM) and its precursors (NO_x, SO_x, NH_3).

PEF report – Document that summarises the results of the PEF study.

PEF study of the representative product (PEF-RP) – PEF study carried out on the representative product(s) and intended to identify the most relevant life cycle stages, processes, elementary flows, impact categories and any other major requirements needed for to define the benchmark for the product category/ sub-categories in scope of the PEFCR.

PEF study – term used to identify all the actions needed to calculate the PEF results. It includes the modelling, data collection and analysis of the results. PEF study results are the basis for drafting PEF reports.

Photochemical ozone formation – EF impact category that accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) and sunlight.

High concentrations of ground-level tropospheric ozone damage vegetation, human respiratory tracts and manmade materials, by reacting with organic materials.

Primary data – data from specific processes within the supply chain of the user of the PEF method or user of the PEFCR.

Such data may take the form of activity data, or foreground elementary flows (life cycle inventory). Primary data are site-specific, company-specific (if multiple sites for the same product) or supply chain specific.

Primary data may be obtained through meter readings, purchase records, utility bills, engineering models, direct monitoring, material/product balances, stoichiometry, or other methods for obtaining data from specific processes in the value chain of the user of the PEF method or user of the PEFCR.

In this method, primary data is a synonym of 'company-specific data' or 'supply chain specific data'.

Product – any good or service.

Product category – group of products (or services) that can fulfil equivalent functions.

Product environmental footprint category rules (PEFCRs) – product category-specific, life cycle-based rules that complement general methodological guidance for PEF studies by providing further specification for a specific product category.

PEFCRs help to shift the focus of the PEF study towards those aspects and parameters that matter most, and hence increase the relevance, reproducibility and consistency of the results by reducing costs, compared to a study based on the comprehensive requirements of the PEF method.

Only PEFCRs developed by or in cooperation with the European Commission, or adopted by the Commission or as EU acts, are recognised as being in line with this method.

Representative product (model) – this may be a real or virtual (non-existing) product. The virtual product should be calculated based on average European market sales-weighted characteristics for all existing technologies/materials covered by the product category or sub-category. Other weighting sets may be used, if justified – for example weighted average based on mass (ton of material) or weighted average based on product units (pieces).

Resource use, fossil – EF impact category that addresses the use of non-renewable fossil natural resources (e.g. natural gas, coal, oil).

Resource use, minerals and metals – EF impact category that addresses the use of non-renewable abiotic natural resources (minerals and metals).

Review – procedure intended to ensure that the process of developing or revising a PEFCR has been carried out in accordance with the requirements provided in the PEF method and part A of Annex II.

Sample – a subset containing the characteristics of a larger population. Samples are used in statistical testing when population sizes are too large for the test to include all possible members or observations. A sample should represent the whole population and not reflect bias toward a specific attribute.

Secondary data – data that is not from a specific process within the supply-chain of the company performing a PEF study.

This refers to data that is not directly collected, measured or estimated by the company, but rather sourced from a third party LCI database or other sources.

Secondary data includes industry average data (e.g., from published production data, government statistics and industry associations), literature studies, engineering studies and patents) and may also be based on financial data, and contain proxy and other generic data.

Primary data that go through a horizontal aggregation step are considered to be secondary data.

Sensitivity analysis – systematic procedures for estimating the effects of the choices made regarding methods and data on the results of a PEF study.

Single overall score – sum of the weighted EF results of all environmental impact categories.

Supply chain – all of the upstream and downstream activities associated with the operations of the user of the PEF method, including the use of sold products by consumers and the end-of-life treatment of sold products after consumer use.

System boundary – definition of aspects included or excluded from the study. For example, for a ‛cradle-to-grave‛ EF analysis, the system boundary includes all activities ranging from the extraction of raw materials, through processing, distribution, storage and use, to the disposal or recycling stages.

System boundary diagram – graphic representation of the system boundary defined for the PEF study.

Temporary carbon storage – this happens when a product reduces the greenhouse gases in the atmosphere or creates negative emissions, by removing and storing carbon for a limited amount of time.

Upstream – occurring along the supply chain of purchased goods/ services prior to entering the system boundary.

Waste – substances or objects which the holder intends (or is required) to dispose of.

Water use – EF impact category that represents the relative available water remaining per area in a watershed, after demand from humans and aquatic ecosystems has been met. It assesses the potential for water deprivation, to either humans or ecosystems, based on the assumption that the less water remaining available per area, the more likely it is that another user will be deprived.

Weighting – a step that supports the interpretation and communication of the analysis results. PEF results are multiplied by a set of weighting factors (in %), which reflect the perceived relative importance of the impact categories considered. Weighted EF results may be directly compared across impact categories, and also summed across impact categories to obtain a single overall score.

1 Summary

This representative product study was done in the context of the development of a methodology for calculating the environmental footprint of fresh fruits and vegetables; the Product Environmental Footprint Category Rules for fresh Fruits and Vegetables (FreshProducePEFCR, see Weststrate et al., 2024). The results of this study feed into the method development for the FreshProducePEFCR, by identifying the most relevant impact categories, life cycle stages, processes and direct elementary flows for the sub-category vegetables, as well as by identifying data needs, data collection activities and data quality requirements for the sub-category vegetables.

The representative product is a virtual (i.e. non-existing) product that reflects the average consumption of vegetables (in kg/capita/year) at the European market. The representative product consists of tomatoes cultivated in Italy (22%), tomatoes cultivated in Spain (17%), tomatoes cultivated in the Netherlands (3%), cabbages cultivated in Poland (30%), carrots cultivated in the Netherlands (20%), green beans cultivated in France (3%) and mushrooms cultivated in the Netherlands (1%).

It should be noted that the virtual representative product does carry the risk that products and technologies with a relative low market share are overlooked, therefore the results of this study cannot be used to make statements about the environmental impact of the product-category vegetables as such. No data quality rating has been applied in this study yet. This study is also not intended to be used in context of comparisons or for comparative assertions to be disclosed to the public.

The impact of 1 kilogram consumable vegetables is calculated, this excludes the inedible parts of the vegetable. The study has a cradle-to-grave approach, meaning all stages of a vegetable’s life cycle are covered. A further split is applied: raw materials, pre-processing and starting materials; cultivation; post-harvest treatment, storage and handling; distribution; consumer packaging; retail; use; end-of-Life. Product dependent and independent processes are excluded from the use phase, but inedible food losses are considered for comparability reasons.

The life cycle inventory (LCI) has been compiled from a combination of company specific data and secondary data. Where no company specific data was available, secondary data sources such as academic literature and databases have been used. the Environmental Footprint life cycle impact assessment method version 3.1 was used to translate the emissions and resource extractions compiled in the LCI, into environmental impacts.

The characterised, normalised and normalised and weighted results are shown in **Table 1**.

Table 1 *Characterised, normalised and weighted results of the virtual representative product*

Impact category	Unit	Characterized result (unit)	Normalized result (person-year)	Weighted result (µPt)
Acidification	mol H^+ eq	5.58E-03	1.00E-04	6.22
Climate change	kg CO_2 eq	5.31E-01	7.03E-05	14.80
Ecotoxicity, freshwater	CTU_e	7.16E+00	1.26E-04	2.43
Particulate matter	disease inc.	4.06E-08	6.81E-05	6.11
Eutrophication, marine	kg N eq	2.78E-03	1.42E-04	4.21
Eutrophication, freshwater	kg P eq	2.33E-04	1.45E-04	4.06
Eutrophication, terrestrial	mol N eq	1.62E-02	9.17E-05	3.40
Human toxicity, cancer	CTU_h	2.12E-10	1.23E-05	0.26
Human toxicity, non-cancer	CTU_h	4.34E-09	3.37E-05	0.62
Ionising radiation	kBq U^{235} eq	3.64E-02	8.62E-06	0.43
Land use	Pt	2.11E+01	2.57E-05	2.04
Ozone depletion	kg CFC11 eq	2.10E-07	4.02E-06	0.25
Photochemical ozone formation	kg NMVOC eq	2.19E-03	5.37E-05	2.57
Resource use, fossils	MJ	6.29E+00	9.68E-05	8.05
Resource use, minerals and metals	kg Sb eq	6.22E-06	9.78E-05	7.38
Water use	m^3 depriv.	6.49E-01	5.66E-05	4.82

A hotspot analysis was conducted to determine what the main contributing elements are to the environmental impact of vegetables. This hotspots analysis is used to determine data needs and data collection activities. The hotspot analysis results in an overview of the most relevant impact categories, life cycle stages, processes and direct elementary flows.

Impact categories that together contribute to at least 80% of the single overall score (ranked from high to low) are identified as most relevant impact categories. The most relevant impact categories identified in this study are:

- Climate Change;
- Resource use, fossils;
- Resource use, mineral and metals;
- Acidification;
- Particulate matter;
- Water use;
- Eutrophication, marine; and
- Eutrophication, freshwater.

Life cycle stages that together contribute more than 80% to that impact category are identified as most relevant life cycle stage. The most relevant life cycle stages identified in this study are:

- Stage 1. Raw materials, pre-processing and starting materials;
- Stage 2. Cultivation;
- Stage 3. Post-harvest treatment, storage, and handling;
- Stage 4. Distribution;
- Stage 5. Consumer packaging;
- Stage 7. Use stage.

Data needs and data collection activities for the product category Vegetables have been identified based on this study. Data needs and data collection activities can be found in the 1st draft of the FreshProducePEFCR.

The aim of the study has been achieved: the most relevant impact categories, life cycle stages, processes and direct elementary flows have been identified. These inform the data needs and data collection activities for the FreshProducePEFCR. The major recommendations from this study are to conduct a sensitivity analysis using a higher tier level for nitrogen and phosphorus modelling, to investigate whether the emission modelling and allocation approach for compost and casing materials are feasible and to investigate the usability of the results to be used as a benchmark for the product category vegetables.

2 General information

This representative product (RP) study is carried out in context of developing harmonised calculations rules to calculate the environmental footprint of fresh fruits and vegetables consumed at the European market. The study is conducted in line with the 1st draft of FreshProducePEFCR (Weststrate et al., 2024) and aims to align with Annex I and II of the Recommendation on the use of the Environmental Footprint methods from the European Commission (2021) wherever possible. This RP study on vegetables is one of the two RP studies that have been selected. The other study is on fruits (Weststrate et al, 2024).

The representative product for vegetables is composed of a virtual product, that reflects the average consumption (in kg/capita/year) of vegetables at the European market. This approach covers all products in the sub-category vegetables according to the product classification (CPA) included in the 1st draft of the FreshProducePEFCR (Weststrate et al., 2024). More general information of this study is shown in **Table 2**.

Table 2 *General information representative product study vegetables*

Information	Description
Name of the product	Virtual Representative Product for vegetables
Product identification	Not applicable
Product classification:	See images 1 to 5 below

Image 1 – Tomato
representative for: other fruit bearing vegetables (CPA 01.13.34)

Image 2 – Cabbage
representative for: leafy and stem vegetables (CPA 01.13.12)

Image 3 – Carrot
representative for: root, bulb and tuberous vegetables (CPA 01.13.41)

Image 4 – Green bean
representative for: green leguminous vegetables (CPA 01.11.6)

Image 5 – White mushroom
representative for: mushrooms (CPA 01.13.8)

Company presentation:	Organisations who have delivered data for this study remain confidential
Date of publication of the PEF study	March 2024
Geographic validity of the PEF study	European market
Compliance with the PEF method	As much as possible aligned with Annex 1 & 2 of the Recommendation on the use of the Environmental Footprint Methods from the European Commission (2021)
Conformance to other documents (additional to the PEF method)	The work in this report is largely based upon previous work carried out in Public Private Partnership “HoritFootprint” that launched the first version of the FloriPEFCR (Broekema et al., 2024) and HortiFootprint Category Rules (Helmes et al., 2020). The Growing Media Environmental Footprint Guidelines V1.3 is used to model the production and emissions for growing media (GME, 2021).

3 Goal of the study

The goal of this 1st study of the representative product (RP study) is to perform an environmental footprint study for vegetables that is the basis for the 1st draft of the FreshProducePEFCR (Weststrate et al., 2024). The first RP study helps to:

- Identify the most relevant impact categories for the sub-category vegetables;
- Identify the most relevant life cycle stages, processes and direct elementary flows for the sub-category vegetables;
- Identify data needs, data collection activities and data quality requirements for the sub-category vegetables.

The target audience of this study are the members of the Technical Secretariat responsible for developing the FreshProducePEFCR, members of Freshfel Europe's Environmental Footprint Initiative (Freshfel Europe, 2023) and stakeholders in the wider fruits and vegetables sector.

The commissioner of this study is the Technical Secretariat of the FreshProducePEFCR, consisting of Freshfel Europe, Fresh Produce Centre the Netherlands, Dole and Greenyard. The Technical Secretariat is part of the wider consortium, consisting next to the aforementioned parties of Royal FloraHolland, Glastuinbouw Nederland, ABN AMRO Bank N.V., Rabobank, Stichting MPS and AQS Holding. The Technical Secretariat and consortium are technically supported by experts from Wageningen Economic Research, PRe Sustainability and Blonk Sustainability, who all together complete the entire consortium of parties contributing to this project. The latter three parties have worked on either drafting or reviewing the LCA models and/or the report. This report is shared with the review panel and during the 1st Public Consultation as supplementary material.

4 Scope of the study

The scope of the study describes the analysed system in detail and addresses the overall approach used to establish (I) the functional unit and reference flow, (II) system boundaries, (III) list of EF impact categories, (IV) additional environmental and technical information and (V) assumptions and limitations.

4.1 Description of the product under study

The representative product for vegetables is composed of a virtual (i.e. non-existing) product, that reflects the average consumption of vegetables (in kg/year/capita) at the European market. The virtual representative product is constructed according to the following corresponding CPA codes:

- CPA 01.13.34: other fruit bearing vegetables;
- CPA 01.13.12: leafy and stem vegetables;
- CPA 01.13.41: root, bulb and tuberous vegetables;
- CPA 01.11.6: green leguminous vegetables;
- CPA 01.13.8: mushrooms.

These CPA codes together represent the entire product category for vegetables. The full list of CPA codes relevant for this product category can be found in section 3.2 of the 1st draft of the FreshProducePEFCR (Weststrate et al, 2024).

Within each of the sub-categories listed above, there is still a large variation of products, production systems, management practices, producing countries, transport modalities etc. To construct the representative product, the product dominating the consumption per capita at the European market (in kg/year for period: 2017-2021) in each sub-category was selected. Consumption per capita is calculated based on data from FAOSTAT (production, population) and EUROSTAT (trade). The selected products were then traced back to country of origin. After raking in decreasing order of production volume (kg), the countries were selected that together reflect 50% of the total EU consumption (kg), starting from the top of this list. The resulting preliminary construction of the RP was consulted with the Technical Secretariat after which some minor adjustments were made to better reflect realistic market conditions and/or cultivation characteristics. **Table 3** lists the selected products including relevant characteristics.

Table 3 *Products and producing countries selected per sub-category including a description of the most relevant characteristics of the product*

Sub category	Product	Country	Description
Fruit bearing vegetables	Tomatoes	Italy	Annual crop, grown in open field in soil
		Spain	Annual crop, grown in greenhouse (type multi-tunnel) in soil (using expanded clay and sand as growing media)
		The Netherlands	Annual crop, grown in glasshouse (type Venlo) outside soil (using stone wool as growing media), year-round production
Leafy and stem vegetables	Cabbage	Poland	Annual crop, grown in open field in soil, long storage
Root, bulb and tuberous vegetables	Carrots	The Netherlands	Annual crop, grown in open field in soil, long storage
Green leguminous vegetables	Green beans	France	Annual crop, grown in open field in soil, N-fixing crop
Mushrooms	White mushrooms	The Netherlands	Annual crop – short production cycle, protected cultivation, outside soil (using casing and compost as growing media), year-round production

The environmental impact of the virtual product is calculated based on the market shares (in kg) of each sub-category the vegetable is representing. Market shares are based on the average consumption of vegetables in kilograms, per capita-year at the European market. In case more than one producing country is selected to ensure representativeness, the selected producing countries are (re)scaled based on the relative shares of the total consumption (kg) of that product. Included market shares are illustrated in **Figure 1**.

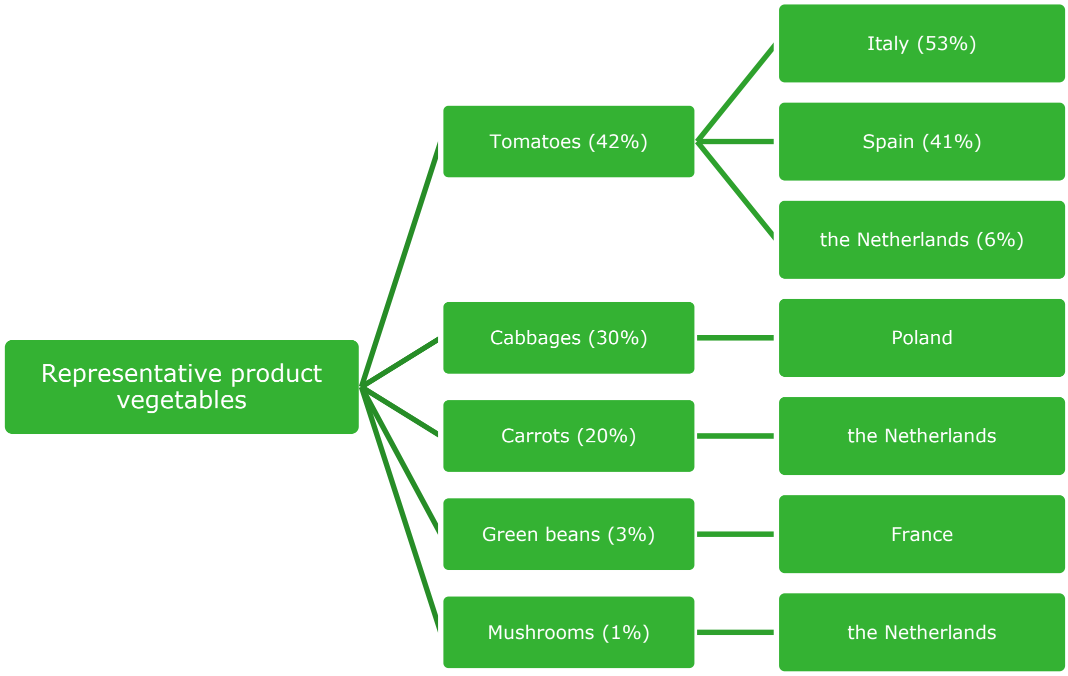

Figure 1 *Composition of the representative product, including market shares that are used to calculate the environmental impact (percentages may not add up to 100% due to rounding). Market shares are based on the average consumption in kilograms, per capita-year at the European market.*

4.2 Functional unit and reference flow

The functional unit (FU) is the quantified performance of a product system, to be used as reference unit. The functional unit qualitatively and quantitatively describes the function(s) and duration of the product in scope. The reference flow is the amount of product needed to provide the defined function. All other input and output flows in the analysis quantitatively relate to it.

The functional unit in this study is 1 kilogram of consumable vegetables (i.e. excluding inedible parts), excluding preparation. Neither product independent (i.e., processes that have no relationship with the way the product is designed or used) or dependent (i.e., processes that are directly or indirectly determined or influenced by the product design or are related to instructions for using the product) processes in the use phase are included in this study. The reason for excluding these processes is that behaviour (e.g., preparation and storage) can vary across consumers and countries, and no sufficient data was available to gain insights in this behaviour to design a meaningful default scenario. Exclusion of inedible food parts (e.g. stem) from the functional unit means additional consumable food parts are needed to fulfil the functional unit. This approach allows comparability between products with different levels of edibility within the product category.

The nutritional content might possibly better reflect the primary functionality of vegetables. However, the current state of science does not yet allow for fair comparisons taking into account the full pallet of nutritional properties. Since comparisons are made within the product category of vegetables and it is expected that the nutritional properties will not be at the heart of comparisons within this category, the functional unit of 1 kilogram is selected.

More characteristics of the functional unit are explained in **Table 4**.

Table 4 *Characteristics of the functional unit*

Aspect	Description
What?	To provide nutrition to humans
How much?	1 kilogram of consumable product, excluding preparation
How well?	According to the specification on consumer packaging or information otherwise known by the consumer related to the characteristics of the specific product
How long?	According to the specification of the producer or the retailer and in accordance with the system boundary

Food losses at post-harvest treatment, storage, handling, distribution, consumer packaging and retail are quantified. It should be noted that the type of packaging might affect the shelf-life of vegetables. The Technical Secretariat did not find sufficient data or methods to integrate this aspect into the functional unit satisfactorily.

4.3 System boundary

The following life cycle stages and processes are included in the system boundary: the entire life cycle (from cradle to grave) of vegetables including the raw material production, pre-processing and starting materials, cultivation, post-harvest treatment, storage and handling, distribution, consumer packaging, retail, use and End-of-Life. A system boundary diagram is shown in **Figure 2**. **Table 5** lists activities included in each life cycle stage.

Figure 2 *Life cycle stages and processes included in the system boundaries. The truck icon means that transport of the materials to location is considered.*

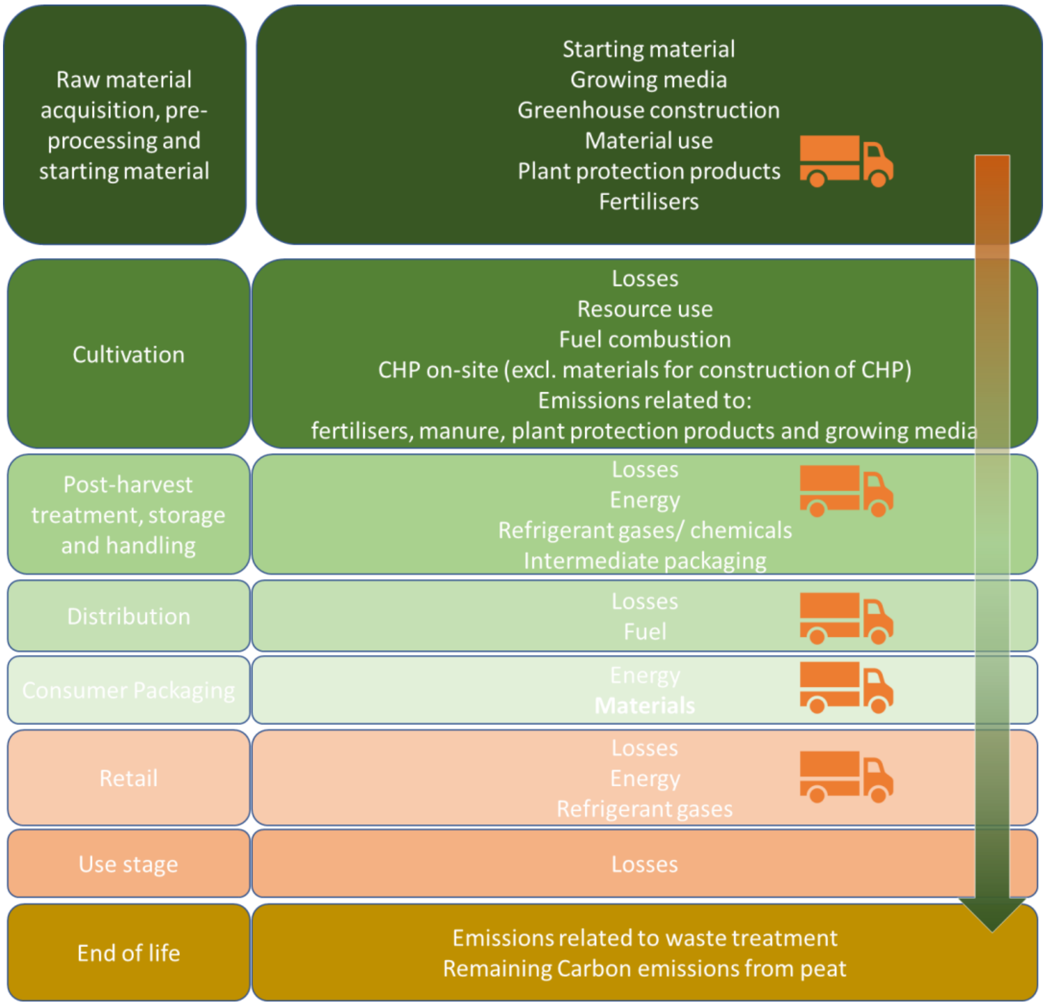

Table 5 *Life cycle stages included*

Life cycle stage	Description of included activities
Raw material production, pe-processing and starting materials	Considers all materials acquired for the cultivation stage (e.g., starting materials, fertilizers, plant protection products), incl. transport to farm. Greenhouse constructions have been included, other capital goods are not included in the analysis.
Cultivation	Considers all activities related to the cultivation, including, but not limited to: plot preparation, planting/sowing, growing and harvesting the vegetables. Emissions from (the use of) plant protection products, fertilizers, growing media, land use and land use change, and peat oxidation are considered in this life cycle stage. The additional quantity to be cultivated for products that are going to processing industry, is accounted for in this life cycle stage.
Post-harvest treatment, storage and handling	Considers all activities related to the post-harvest treatment, storage and handling of the product, including, but not limited to: transport from cultivation to storage or post-harvest treatment location, utility use, waste water treatment, chemical production and use, refrigerant use, intermediate packaging production, and waste (incl. the additional quantity needed to fulfil the FU). These activities might take place at different locations along the value chain, but shall all be accounted for in this life cycle stage.
Distribution	Considers all activities related to delivering the product to the final consumer, including but not limited to: all transport legs from post-harvest treatment and/or storage facility to the final consumer, utility use at the distribution centre (DC), waste of secondary and tertiary packaging and waste (incl. the additional quantity needed to fulfil the FU).
Consumer packaging	Considers all activities related to the production of packaging materials for consumer packaging (primary, secondary, tertiary), utility use for packaging operations, transport of packaging materials to location and waste of intermediate packaging.
Retail	Considers utility use (e.g., electricity and water) and waste (incl. the additional quantity needed to fulfil the FU).
Use	Considers the waste of the inedible parts of the vegetable (incl. the additional quantity needed to fulfil the FU).
End-of-Life	Considers the End-of-Life of the primary packing material and remaining Carbon emissions from growing media.

4.4 Environmental Footprint impact categories

The Environmental Footprint (EF) impact assessment method documented in the most recent version of the PEF method is used, namely version 3.1. **Table 6** lists all EF impact categories, impact category indicators, units and their respective characterization models included. The characterisation methods provide in characterization factors that express how much a single unit of mass of the intervention contributes to an impact category. The full list of characterisation factors is available at https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

Table 6 List of EF impact categories with respective impact category indicators and characterisation models

EF Impact category	Impact Category Indicator	Unit	Characterization model	Robustness
Climate change (total) *Sub-category[2]:* • Biogenic • Fossil • Land use and LU change	Radiative forcing as global warming potential (GWP100)	kg CO_2 eq	Bern model – Global warming potentials (GWP) over a 100-year time horizon (based on IPCC, 2021).	I
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	EDIP model based on the ODPs of the World Meteorological Organisation (WMO) over an infinite time horizon (WMO 2014 + integrations)	I
Human toxicity, cancer	Comparative Toxic unit for humans (CTU_h)	CTU_h	Based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018	III
Human toxicity, non-cancer	Comparative Toxic unit for humans (CTU_h)	CTU_h	Based on USEtox2.1 model (Fantke et al. 2017), adapted as in Saouter et al., 2018	III
Particulate matter	Impact on human health	Disease incidence	PM model (Fantke et al., 2016 in UNEP 2016)	I
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235} eq	Human health effect model as developed by Dreicer et al 1995 (Frischknecht et al, 2000)	II
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTUS-EUROS model (Van Zelm et al, 2008) as applied in ReCiPe 2008	II
Acidification	Accumulated Exceedance (AE)	mol H^+ eq	Accumulated exceedance (Seppälä et al. 2006, Posch et al, 2008)	II
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated exceedance (Seppälä et al. 2006, Posch et al, 2008)	II
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) as applied in ReCiPe	II
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) as applied in ReCiPe	II
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTU_e	Based on USEtox2.1 model (Fantke et al. 2017, adapted as in Saouter et al., 2018)	III
Land use	• Soil quality index[3] • Biotic production • Erosion resistance • Mechanical filtration • Groundwater replenishment	• Dimensionless (pt) • kg biotic production • kg soil • m^3 water • m^3 groundwater	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)	III
Water use	User deprivation potential (deprivation weighted water consumption)	m^3 world eq	Available WAter REmaining (AWARE) as recommended by UNEP 2016	III
Resource use[4], minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML 2002 (Guinée et al. 2002 and Van Oers et al. 2002)	III

Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	Van Oers et al., 2002 as in CML methods, v.4.8.	III

Normalisation and weighting are required steps of the Life Cycle Impact Assessment (LCIA). Those steps allow expressing LCA results aggregating the results up to a single score, giving different weight to the different environmental impacts. The full list of normalisation factors and weighting factors are available in **Annex 1**.

Although all listed EF impact categories are included in the calculation of the weighted results, it is important to mention that the different impact categories are not equally robust. The European Commission classifies the EF impact categories into three groups, from more robust (I) to less robust (III). The robustness of the impact categories is indicated in column 5 of **Table 6**. The differences in robustness have been taken into account in the weighting factors provided by the European Commission and should also be taken into account during interpreting the results of study.

4.5 Additional information

Relevant potential environmental impacts that may go beyond the EF impact categories are, whenever feasible, reported as additional environmental information. As per 1st draft of the FreshProducePEFCR information on biodiversity and carbon and nutrient content of growing media is reported here.

Biodiversity
Biodiversity is considered as relevant for this representative product study. However, the PEF method does not include any impact category named 'biodiversity', as currently there is no consensus on an LCIA method capturing that impact. However, the PEF method includes at least eight impact categories that have an effect on biodiversity (i.e. climate change, eutrophication (aquatic freshwater), eutrophication (aquatic marine), eutrophication (terrestrial), acidification, water use, land use and ecotoxicity (freshwater)).

The topic is under discussion within the Agricultural Working Group of the European Commission, the 1st draft of the FreshProducePEFCR (Weststrate et al, 2024) is following the developments and intends to update once the issue is addressed.

Carbon and nutrient content of growing media
Carbon and nutrient content of growing media shall be reported based on product-specific data according to the 1st draft of the FreshProducePEFCR. this information includes the bulk density of the final growing media, the carbon content of the peat-based constituents in the growing media in kg C/m^3 as delivered to the client, the nutrient content (NPK) of the growing media, and the nutrient (NPK) and limestone content of each additive in kg/m^3.

4.6 Assumptions and limitations

Assumptions
All assumptions made during modelling are documented and reported in the LCI tables and/or section 5.2.

[2] The EF impact category "Climate Change, total" is constituted of three sub-categories: Climate Change, fossil; Climate Change, biogenic; Climate Change, land use and land use change. The sub-indicators are only reported separately if they show a contribution of more than 5% each to the total score of climate change.
[3] This index is the result of the aggregation, performed by JRC, of the 4 indicators provided by LANCA model as indicators for LU.
[4] The results of this impact category shall be interpreted with caution, because the results of ADP after normalization may be overestimated. The European Commission intends to develop a new method moving from deletion to dissipation model to better quantify the potential for conservation of resources.

Limitations

There are limitations related to agricultural modelling that need further improvement:

- Modelling of emissions of crop protection products, e.g., missing characterisation factors and LCI modelling of emissions;
- Country-specific characterisation factors for nitrogen and phosphorus emissions in eutrophication are only available for EU countries however cultivation can happen worldwide;
- Modelling of nitrogen and phosphorus emissions due to the application of fertilizers;
- More granularity in the regionalisation of water flows for a proper assessment of water scarcity;
- Quality biodiversity impacts that go beyond impacts not covered in the current list of impact categories;
- The production and application of biological pest control cannot be captured because of missing background information.

There are also limitations related to modelling life cycle stages further downstream in the life cycle:

- Product loss and waste may vary along the food supply chain, depending on e.g., product type, practices (e.g., cooling), packaging, and geographical region. The PEF method prescribes a default of 10% for both distribution and retail, but does not indicate in what life cycle stage the losses should be attributed to, nor does it account for different geographies, packaging, product types or practices. To solve the attribution part, retail specific food losses are collected (see section 5.2).
- Product density (excluding packaging) is used to allocate volume based impacts, instead of density including the packaging due to lacking data.
- In context of PEF, the recycled content and end of life is modelled using the circular footprint formula (CFF). In this study, the CFF is not applied purely on the material input side. The application of the CFF in end-of-life faces also several shortcomings, e.g. not including actual recycling processes or processes that contain some recycled content (e.g., steel, iron).
- Transport distances to market (e.g., point of sale) in background processes are not modelled PEF-compliant in terms of transport distance and/or modality (see section 5.2).

There are limitations related to the composition of the representative product study:

- Technologies (e.g., residual heat) and transportation modes (e.g., airfreight) with a relatively low market share might be overlooked. The share of technologies and transportation modes in the overall consumption can be limited, whilst the environmental impact as share of the consumption they represent can be higher.
- Alternative production systems (e.g., regenerative, organic) are not included in this analysis;
- In practice there is a large variety of products, production countries and systems etc. The absolute results of this RP study cannot be regarded as representative, but it is assumed that the general conclusions give a satisfactory indication of the hotspots (life cycle stages, impact categories, processes, (direct) elementary flows).

Due to its composition and limitations, the results of this study cannot be used to make statements about the sub-category vegetables as such, nor is it intended to be used in the context of comparison or for comparative assertions to be disclosed to the public.

5 Life Cycle Inventory Analysis

5.1 List and description of life cycle stages

For an overview and description of the life cycle stages see section 4.3. In ***Table 7*** a summarised overview of all considered inputs and outputs modelled is given. Please note that not all activities are applicable to all products part of the virtual representative product. The exact activity data and background processes used remain confidential in this RP report.

Table 7 *Overview of included activities per life cycle stage*

Life cycle stage	Activities
Raw material production, pe-processing and starting materials	• Production and transport of starting materials; • Production and transport of fertilizers; • Production and transport of plant protection products; • Production and transport of greenhouse construction;; • Production and transport of growing media; • Production and transport of packaging used by transport to post-harvest and/or storage facility.
Cultivation	• Use of natural resources, e.g. land occupation, water; • Energy use, incl. energy used for generating heat and/or electricity; • Fuel use[5]; • Emissions from fertilizers and manure, lime, urea and plant protection products; • Emissions related to land transformation (e.g., deforestation) and land management; • Emissions from the use of growing media and additives.
Post-harvest treatment, storage and handling	• Transport from farm to post-harvest treatment and/or storage facility; • Production and emissions of refrigerant gasses; • Production and emissions of chemicals used in post-harvest treatment and storage; • Production and transport of intermediate packaging; • Electricity, heat and water use at post-harvest treatment and/or storage facility; • Moisture losses; • Waste (treatment) of physical product losses.
Distribution	• Transport from post-harvest treatment facility to port of departure OR DC • Transport from port of departure to port of arrival; • Transport from port of arrival to DC • Transport from DC to retail; • Transport from retail to consumer; • Electricity, heat and water use at distribution centre; • Waste (treatment) of physical product losses.
Consumer packaging	• Production and transport of primary, secondary and tertiary packaging material; • Electricity, heat and water use at packaging facility; • Waste treatment of intermediate packaging; • Waste (treatment) of physical product losses.
Retail	• Electricity and water use at retail; • Waste (treatment) of secondary and tertiary packaging materials; • Waste (treatment) of physical product losses.
Use stage	• Waste (treatment) of physical inedible product losses.
End-of-Life	• Waste treatment of primary packaging materials; • Remaining carbon emissions from growing media.

[5] The background database used does include the production of fuel in the combustion process, therefore the production and combustion of fuels are both included in the cultivation phase. This is different

5.2 Modelling choices

All modelling choices are made in accordance with the 1st draft of the FreshProducePEFCR (Weststrate et al, 2024). The following sub-paragraphs lists the most relevant modelling choices.

Agricultural production:

- Wherever possible, an assessment period of three years is used to level out differences in crop yields related to fluctuations in growing conditions over the years such as climate, pests and diseases, etc. For perennial plants, a steady state situation (i.e. where all developments stages are proportionally represented in the studied time period) is constructed.
- Emissions from pesticides are modelled per specific active ingredient using a default fraction to agricultural soil (90%), air (9%) and water (1%). Active ingredients not characterised in the EF-LCIA method are omitted. This might lead to an underestimation of the toxicity impacts related to pesticide application.
- Emissions resulting from the application of fertilisers are modelled using the default modelling approach as prescribed in the 1st draft of the FreshProducePEFCR (Weststrate et al, 2024). The following emissions are modelled:
    - Ammonia volatilisation (to air), based in IPCC Tier 1 (incl. NO_x-emissions);
    - Direct and indirect nitrous oxide (to air), based on IPCC Tier 1;
    - Carbon dioxide from lime, urea and urea-compound application (to air), based on IPCC Tier 1;
    - Nitrate (to water), based on IPCC Tier 1;
    - Phosphorus (to soil), based on PEF-method (EC, 2021).
- The following emissions resulting for the use of growing media and additives are modelled using the modelling approach as prescribed in the 1st draft of the FreshProducePEFCR (Weststrate et al, 2024) and Growing Media Europe Environmental Footprint Guidelines V1.3 (GME, 2021):
    - Ammonia volatilisation (to air), based on IPCC Tier 1 (incl. NO_x-emissions);
    - Direct and indirect nitrous oxide (to air), based on IPCC Tier 1;
    - Carbon dioxide from lime, urea and urea-compound application (to air), based on IPCC Tier 1;
    - Nitrate (to water), based on IPCC Tier 1;
    - Phosphorus (to soil), based on PEF method (EC, 2021).
- The carbon content of the peat constituents in growing media are assumed to be oxidised into CO_2 at a default oxidation rate of 5% of the peat carbon content per year. At the point of transfer to EoL, full oxidation of remaining C in peat constituent is assumed and reported in EoL.
- Nitrogen, phosphorous, and CO_2-related emissions from additives and growing media nutrient content is assumed to be fully emitted and attributed to the user of the growing media, regardless of whether the growing media is reused at a later stage.
- The uptake of heavy metals by vegetables is not considered.
- CO_2 emissions resulting from the application of purchased CO_2 in greenhouses are omitted. The application and emissions of CO_2 during the production are considered as a delaying emission of the providing industry. Activities related to the transport and purification of CO_2 is accounted for.
- The impact of the combined heat and power (CHP) system in greenhouses is allocated to heat and electricity based on the energy content (energy allocation). Apart from the purification process for CO_2, no environmental impacts are allocated to the production of CO_2.
- Emissions related to land occupation and land use change are modelled according to PAS 2050:2011 (BSI, 2011) and the supplementary document PAS2050-1:2012 (BSI, 2012) for horticultural products. All values are retrieved from the dLUC Impact Dataset version 2022 (Blonk Sustainability Tools, 2023).

Distribution:

- Transport distances, load factors and modalities are based on primary data. In case no primary data is available the following defaults are used:
    - 30 km by truck (10-20t, EURO 5) for manure (Blonk Sustainability Tools, 2023);
    - 230 km by truck (>20t, EURO 5), 280 km by freight train (electricity, bulk), 360 km by barge ship (container, 2000t) for (intermediate) packaging materials (based on PEF default);
    - 150 km by truck (10-20t, EURO 5) for all other inputs (assumption).
- Market processes are used wherever available. In case no market process is available, the following default is applied to account for transportation of the materials from various locations to the specific

market: 230 km by truck (>20t, EURO 4), 240 km by train (electricity, bulk) and 270 km by barge ship (container, 2000t). The default is derived from the PEF method (European Commission, 2021) and is applied additionally to the distance from the market (e.g., point of sale) to the end-user (e.g., farmer).
- Fust is assumed to be reused 100 times, pallets are assumed to be reused 30 times. For other packaging materials, no reuse is assumed. The weight of packaging materials has been considered during transport, no correction for the reuse rate is applied.
- Average storage time at distribution centre is assumed to be 2 days (based on expert judgement);
- Average electricity use at distribution centre is assumed to be 0.32 kWh/m^3 for the average storage time (ADEME, 2022), allocation to the product based is done based on the volume of the product;
- Average heat use at distribution centre is assumed to be 3.95 MJ/m^3 for the average storage time (ADEME, 2022), allocation to the product based is done based on the volume of the product;
- Average water use at distribution centre is assumed to be 0.13 l/m^3 for the average storage time (ADEME, 2022), allocation to the product based is done based on the volume of the product.

Capital goods:
- The production of capital goods are not considered, as previous studies have shown they are not a relevant contributor to the overall environmental impact of horticultural products (Kan and Vieira, 2020; Broekema et al., 2024, Helmes et al., 2020). Except for greenhouses, where the materials used to construct these are taken into account.
- Energy and water use of capital goods during its use are included in the inventory data.

Retail:
- Average storage time at retail is assumed to be 1.5 days (based on expert judgement);
- Average electricity use at retail is assumed to be 6.59 kWh/m^3 for the average storage time (ADEME, 2022) for general activities (e.g. lighting) and 46.98 kWh/m^3 for cooling (if applicable), allocation to the product based is done based on the volume of the product;
- Average water use at retail is assumed to be 30.08 l/m^3 for the average storage time (ADEME, 2022), allocation to the product based is done based on the volume of the product;
- The average waste percentage for vegetables at retail is assumed to be 2.1% (Stichting Samen tegen Voedselverspilling, 2023).

Use stage:
- In alignment with the defined functional unit, neither product dependent and independent processes have been modelled.
- For comparability reasons, non-edible food losses (RIVM, 2023) are considered in the reference flow to satisfy the functional unit of 1 kilogram consumable vegetable.

End of life modelling:
- End-of-Life for various materials is modelled using the Circular Footprint Formula (CFF): PP plastic, PE plastic, PS plastic, cardboard/paper, steel, concrete, wood and biowaste.
- The CFF is not applied on the material input side.

Electricity use:
- Electricity use is modelled using the grid mix for the applicable country, unless company-specific data is available.
- For the stages after post-harvest treatment and storage. The average European grid mix is used to ensure representativeness.

Sampling procedure:
- No sampling procedure is applied.

Greenhouse gas emissions and removals:
- Three main categories of greenhouse gases emissions and removals are considered during modelling (I) fossil GHG emissions and removals, (II) biogenic carbon emissions and removals and (III) carbon emissions from land use and land use change.
- No simplified modelling approach was used to model biogenic carbon flows (not applicable);

- Credits associated with temporary and permanent carbon storage and/or delayed emissions are not being considered in the calculation of the climate change indicator. This means that all emissions and removals are considered as emitted 'now' and there is no discounting of emissions over time.

5.3 Handling multi-functional processes

In case of multifunctional processes (i.e., if a product has more than one function), all inputs and emissions linked to the process were partitioned between the product under study and the other co-products according to the allocation rules specified in **Table 8**.

Table 8 *Allocation rules for activity data and elementary flows*

Process	Allocation rule	Modelling instructions	Allocation factor
Allocating organic fertilizer use and green manure in annual open field rotation systems	Organic manure is divided over all crops in the crop rotation scheme on the basis of share in area, expect for the mineral N fraction which is allocated solely to the crop of application	If organic fertiliser is applied in a crop rotation scheme, the following calculation rules apply for fertilisation of N (BSI, 2012). Formula 1 (Calculating N application to a crop as part of a crop rotation scheme) Total N from organic fertiliser applied to the plot where crop A stands (in kg N/ area unit) = NmOA + NcrA +aA/aT x (NoOT+NcrT) Where: • NmOA = mineral nitrogen from organic fertiliser applied to crop A (kg N/ area unit) • NcrA = nitrogen from residues of crop A (kg N/ area unit) • aA = area of crop A (area unit) • aT = total area of rotation system (area unit) • NoOT = organic nitrogen from organic fertiliser applied on all area (kg N/ area unit) • NcrT = nitrogen from crop residues of green manure on all area (kg N/ area unit) All other fertilising elements supplied using organic fertilisers, including green manure, is calculated by formula 2. Formula 2: (Calculating fertiliser application to a crop as part of a rotation scheme) Fapplied to crop A = aA/aT x (FOT) Where: • Fapplied to crop A = fertliser applied to crop A • aA = area of A (area unit) • aT = total area of rotation system (area unit) • FOT = organic fertiliser applied on all area (kg F/area unit)	
Organic fertilisers	Manure used in conventional farming is considered as a zero-burden product unless farmers need to pay a price for the manure that exceeds transport costs. Manure is then treated as a co-product where economic allocation shall be used. If the animal farmer needs to pay a price to the party receiving the manure, it is treated as residual product. Economic allocation shall be applied for all other organic fertilisers originating from industrial processes.	For manure, as a zero-burden product, all activities needed after storage at the animal farm to application on the horticulture crop are included (thus including transport and processing if occurring). If manure has a price, then the price will be based on the revenues for the animal farmer (excluding transport costs) or the price will be based on a shadow price derived from equivalent quantities of artificial fertiliser needed.	

Energy use, cleaning and other generic operations in greenhouse cultivation	Land occupation and economic allocation depending on the situation.	When multiple crops are grown in a protected (and heated) system, the relative land occupation of each crop shall be applied to allocate the interventions related to the inputs for which it cannot be specified. When possible, the system should first be broken down in sub-systems, for instance into separated compartments within a greenhouse. Land occupation per crop shall be obtained by specific data for the analysed time period (this will include any changes in land occupation due to differences with planning, differences in production, etc.). When not available, the average land occupation per crop shall be used. This shall be calculated by adding together the land occupation per crop per phase using the following equation: LO = Sum over phases (p) (GTp * 1 / PDp) Where: LO = land occupation (yr*m^2) GTp = growing time of phase p (yr) PDp = crop density of phase p (kg / m^2)
Combined heat and power systems (CHP) in Greenhouse Cultivation	Energy content (energy allocation)	The impact of CHP for the horticultural system shall be calculated by subdividing the heat and electricity produced, based on the energy produced through both. No environmental impact shall be attributed to the production of CO_2 output from the CHP. However, the environmental impacts of the purification process shall be attributed to the produced CO_2. If CHP is turned on for electricity only, then heat should be attributed to the product. (see chapter **Error! Reference source not found.**)
Transport (inbound and outbound)	Physical property defining load capacity	Allocation of transport emissions to transported products shall be done on the basis of physical causality, such as mass share, unless the density of the transported product is significantly lower than average so that the volume transported is less than the maximum load. Allocation of empty transport kilometres shall be done on the basis of the average load factor of the transport that is under study. If no supporting information is available, it shall be assumed that 100% additional transport is needed for empty return, which equals the utility rate of 50% (EC, 2021).
Storage to single product	Volume and time	Only part of the emissions and resources emitted or used at storage systems shall be allocated to the product stored. This allocation shall be based on the space (in m^3) and time (in weeks) occupied by the product stored. For this the total storage capacity of the system shall be known, and the product-specific volume and storage time shall be used to calculate the allocation factor (as the ratio between product-specific volume*time and storage capacity volume*time). Further guidance on emission and resource allocation from storage can be found in (EC, 2021).

5.4 Data collection

This section describes the data collection process and decision hierarchy applied to select data sources. Both company specific data and secondary data are used in this study. To select data-sources, the decision hierarchy as illustrated in **Figure 3** is used to select the type of data-source. The use of representative company-specific data prevails over any other data-source. Data from academic literature prevails over other more general secondary data-sources (statistics etc.).

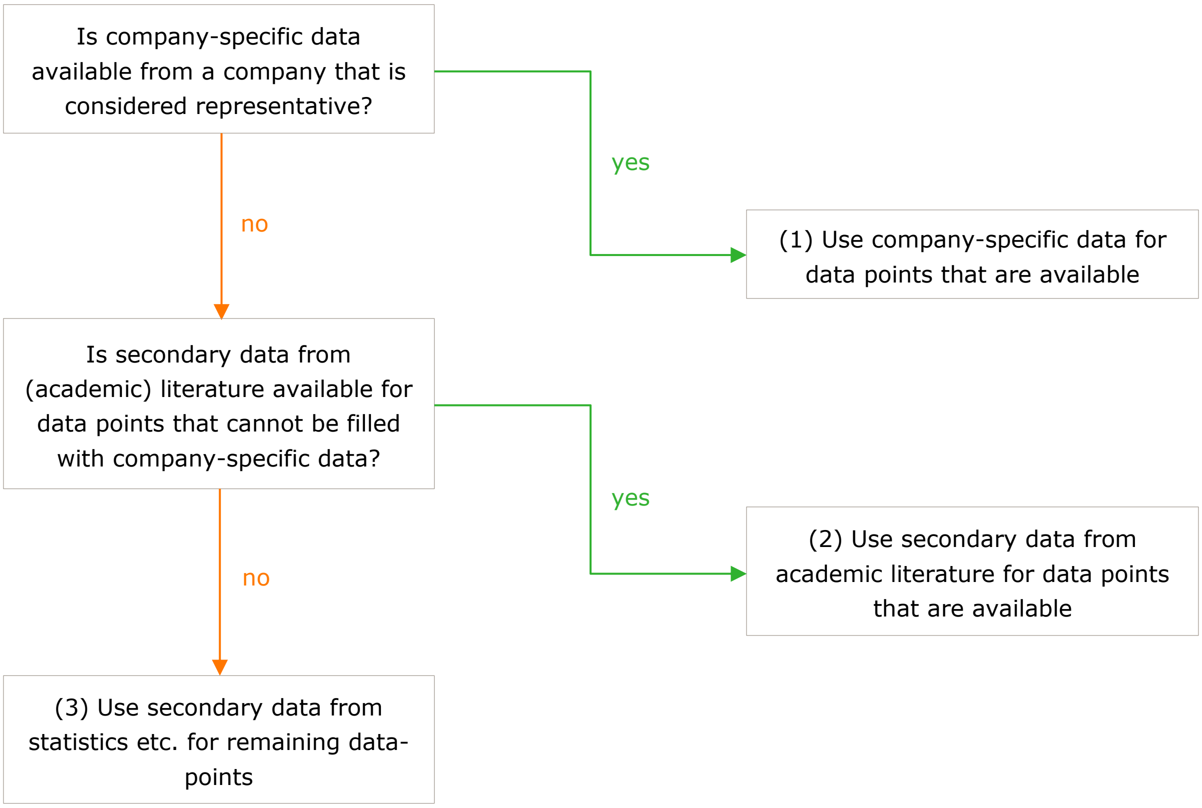

Figure 3 *Decision hierarchy for selection of data sources*

The selection of secondary data sources under point 3 is uniformly applied to similar inputs and outputs for all product under consideration. For example, if data on fertilizer use is not available for product X and Y, the same secondary data-source is used to ensure consistency.

Activity data is coupled to corresponding LCI datasets. The following databases are used:

- ecoinvent 3.9, with the "allocation, cut-off by classification" system model;
- Agri-footprint 6.3, economic allocation;
- Growing Media Europe LCA database.

For some processes currently not in any of the aforementioned databases, new processes have been developed (e.g. CHP system, geothermal heat, waste treatment).

5.5 Data quality requirements and rating

No data quality rating has been applied in this RP study yet. The 1st draft of the FreshProducePEFCR requires to use a dedicated LCI-background database, consisting of processes from several other LCI-databases with different DQR-approaches. This issue will be addressed later on in the project.

6 Life Cycle Impact Assessment Results

6.1 Environmental footprint results

Characterised results per impact category and per life cycle stages are reported as absolute values in **Table 10**. Normalised results as absolute values are reported in **Table 11** and weighted results as absolute values are reported in **Table 12**, where the total of all impact categories is the weighted results as single score. The single score results of 1 kilogram of the consumable representative product for vegetables is 67.75 µPt.

The single score is obtained by first normalizing the characterized results through dividing them by a normalisation factor. The applied normalisation factors are reported in table A.1. The normalised results reflect the burdens that are attributed to a product in relation to the reference unit. Subsequently, the normalised results are multiplied by a set of weighting factors (in %) which reflects the perceived relative importance of the life-cycle impact categories considered. The applied weighting factors are reported in table A.2.

6.2 Additional information

The 1st draft of the FreshProducePEFCR requires to report the carbon and nutrient content of growing media under additional environmental information.

Carbon and nutrient content of growing media
Rockwool is used as growing media for tomato cultivation in the Netherlands, and compost and casing material for white mushroom production in the Netherlands. The bulk density of these growing media, the carbon content of the peat-based constituent in the growing media as delivered to the client, the nutrient content (NPK) of the growing media, and the nutrient (NPK) and limestone content of each additive in kg/m^3 are reported in **Table 9**.

Table 9 *Carbon and nutrient content of growing media*

Rockwool	Quantity	Compost	Quantity	Casing	Quantity
Bulk density (kg/m^3)	46	Dry matter (g/kg)	349	Bulk density (kg/m^3)	343
C content peat (kg C/m^3)	0	C content peat (g C/kg)	0	C content peat (kg C/m^3)	50
N content (kg N/m^3)	0	N content (g N/kg)	20.71	N content (kg N/m^3)	0
P content (kg P/m^3)	0	P content (g P/kg)	5.02	P content (kg P/m^3)	0
Limestone content (kg/m^3)	0	Limestone content (g/kg)	0	Limestone content (kg/m^3)	42

Table 10 *Characterised results of the virtual representative product for all EF impact categories as absolute values per kg of vegetables*

Impact category	Unit	Total	Stage 1. Raw materials	Stage 2. Cultivation	Stage 3. Post-harvest handling and storage	Stage 4. Distribution	Stage 5. Consumer packaging	Stage 6. Retail	Stage 7. Use stage	Stage 8. End-of-life
Acidification	mol H^+ eq	5.58E-03	4.10E-04	2.86E-03	3.37E-04	9.25E-04	3.60E-04	2.10E-04	4.82E-04	-9.34E-06
Climate change	kg CO_2 eq	5.31E-01	6.29E-02	1.19E-01	4.88E-02	1.40E-01	6.98E-02	3.08E-02	5.16E-02	7.48E-03
Ecotoxicity, freshwater	CTU_e	7.16E+00	1.47E+00	3.00E+00	4.54E-01	9.56E-01	2.30E-01	2.50E-01	8.10E-01	-3.08E-03
Particulate matter	disease inc.	4.06E-08	3.93E-09	2.21E-08	2.00E-09	5.12E-09	2.96E-09	1.33E-09	3.15E-09	-2.63E-11
Eutrophication, marine	kg N eq	2.78E-03	6.57E-05	1.69E-03	1.60E-04	4.34E-04	8.21E-05	8.86E-05	2.59E-04	5.63E-07
Eutrophication, freshwater	kg P eq	2.33E-04	1.50E-05	1.09E-04	3.10E-05	1.68E-05	2.70E-05	1.55E-05	2.03E-05	-1.78E-06
Eutrophication, terrestrial	mol N eq	1.62E-02	1.29E-03	7.58E-03	1.02E-03	3.64E-03	8.15E-04	5.24E-04	1.36E-03	-1.24E-05
Human toxicity, cancer	CTU_h	2.12E-10	8.08E-11	2.29E-11	2.60E-11	2.54E-11	3.09E-11	1.14E-11	1.52E-11	-4.13E-13
Human toxicity, non-cancer	CTU_h	4.34E-09	8.63E-10	5.20E-10	7.06E-10	6.15E-10	8.59E-10	3.29E-10	4.47E-10	6.19E-13
Ionising radiation	kBq U^{235} eq	3.64E-02	3.07E-03	3.40E-03	3.52E-03	7.04E-03	1.24E-02	6.65E-03	1.52E-03	-1.28E-03
Land use	Pt	2.11E+01	3.35E+00	1.27E+01	1.50E+00	1.60E+00	3.99E-01	4.69E-01	1.07E+00	-4.27E-03
Ozone depletion	kg CFC11 eq	2.10E-07	4.05E-09	8.20E-09	2.02E-09	3.25E-08	1.49E-07	4.78E-09	9.55E-09	-1.23E-10
Photochemical ozone formation	kg NMVOC eq	2.19E-03	1.82E-04	4.99E-04	2.04E-04	7.79E-04	2.61E-04	1.07E-04	1.68E-04	-6.28E-06
Resource use, fossils	MJ	6.29E+00	8.06E-01	1.05E+00	5.42E-01	1.67E+00	1.51E+00	4.14E-01	3.74E-01	-7.39E-02
Resource use, minerals and metals	kg Sb eq	6.22E-06	8.42E-07	3.94E-07	2.46E-07	3.53E-07	3.83E-06	2.77E-07	2.83E-07	-2.04E-09
Water use	m^3 depriv.	6.49E-01	1.97E-02	4.97E-01	1.78E-02	4.32E-02	2.24E-02	1.89E-02	3.05E-02	-4.69E-04

Table 11 *Normalised results as absolute values (1 person-year reflects the contribution of 1 European citizen for 1 year to the respective impact category)*

Impact category	Unit	Total	Stage 1. Raw materials	Stage 2. Cultivation	Stage 3. Post-harvest handling and storage	Stage 4. Distribution	Stage 5. Consumer packaging	Stage 6. Retail	Stage 7. Use stage	Stage 8. End-of-life
Acidification	person-year	1.00E-04	7.37E-06	5.15E-05	6.07E-06	1.67E-05	6.48E-06	3.79E-06	8.67E-06	-1.68E-07
Climate change	person-year	7.03E-05	8.33E-06	1.58E-05	6.46E-06	1.85E-05	9.25E-06	4.08E-06	6.84E-06	9.91E-07
Ecotoxicity, freshwater	person-year	1.26E-04	2.59E-05	5.28E-05	8.00E-06	1.69E-05	4.06E-06	4.42E-06	1.43E-05	-5.43E-08
Particulate matter	person-year	6.81E-05	6.61E-06	3.71E-05	3.37E-06	8.60E-06	4.98E-06	2.24E-06	5.29E-06	-4.42E-08
Eutrophication, marine	person-year	1.42E-04	3.36E-06	8.64E-05	8.19E-06	2.22E-05	4.20E-06	4.53E-06	1.33E-05	2.88E-08
Eutrophication, freshwater	person-year	1.45E-04	9.31E-06	6.78E-05	1.93E-05	1.05E-05	1.68E-05	9.64E-06	1.26E-05	-1.11E-06
Eutrophication, terrestrial	person-year	9.17E-05	7.28E-06	4.29E-05	5.77E-06	2.06E-05	4.61E-06	2.96E-06	7.71E-06	-7.00E-08
Human toxicity, cancer	person-year	1.23E-05	4.68E-06	1.33E-06	1.51E-06	1.47E-06	1.79E-06	6.61E-07	8.82E-07	-2.40E-08
Human toxicity, non-cancer	person-year	3.37E-05	6.70E-06	4.04E-06	5.48E-06	4.78E-06	6.67E-06	2.55E-06	3.47E-06	4.81E-09
Ionising radiation	person-year	8.62E-06	7.27E-07	8.06E-07	8.33E-07	1.67E-06	2.95E-06	1.58E-06	3.61E-07	-3.03E-07
Land use	person-year	2.57E-05	4.09E-06	1.55E-05	1.84E-06	1.95E-06	4.87E-07	5.73E-07	1.30E-06	-5.22E-09
Ozone depletion	person-year	4.02E-06	7.74E-08	1.57E-07	3.86E-08	6.21E-07	2.85E-06	9.14E-08	1.83E-07	-2.34E-09
Photochemical ozone formation	person-year	5.37E-05	4.46E-06	1.22E-05	5.00E-06	1.91E-05	6.40E-06	2.62E-06	4.11E-06	-1.54E-07
Resource use, fossils	person-year	9.68E-05	1.24E-05	1.61E-05	8.34E-06	2.56E-05	2.33E-05	6.37E-06	5.75E-06	-1.14E-06
Resource use, minerals and metals	person-year	9.78E-05	1.32E-05	6.19E-06	3.87E-06	5.56E-06	6.01E-05	4.36E-06	4.45E-06	-3.21E-08
Water use	person-year	5.66E-05	1.72E-06	4.33E-05	1.55E-06	3.77E-06	1.96E-06	1.65E-06	2.66E-06	-4.09E-08

Table 12 *Weighted results as absolute values (microPoints (µPt) reflect the environmental impact score, as weighted with the EF weighting method)*

Impact category	Unit	Total	Stage 1. Raw materials	Stage 2. Cultivation	Stage 3. Post-harvest handling and storage	Stage 4. Distribution	Stage 5. Consumer packaging	Stage 6. Retail	Stage 7. Use stage	Stage 8. End-of-life
Acidification	µPt	6.22	0.46	3.19	0.38	1.03	0.40	0.23	0.54	-0.01
Climate change	µPt	14.80	1.75	3.33	1.36	3.90	1.95	0.86	1.44	0.21
Ecotoxicity, freshwater	µPt	2.43	0.50	1.01	0.15	0.32	0.08	0.08	0.27	0.00
Particulate matter	µPt	6.11	0.59	3.32	0.30	0.77	0.45	0.20	0.47	0.00
Eutrophication, marine	µPt	4.21	0.10	2.56	0.24	0.66	0.12	0.13	0.39	0.00
Eutrophication, freshwater	µPt	4.06	0.26	1.90	0.54	0.29	0.47	0.27	0.35	-0.03
Eutrophication, terrestrial	µPt	3.40	0.27	1.59	0.21	0.76	0.17	0.11	0.29	0.00
Human toxicity, cancer	µPt	0.26	0.10	0.03	0.03	0.03	0.04	0.01	0.02	0.00
Human toxicity, non-cancer	µPt	0.62	0.12	0.07	0.10	0.09	0.12	0.05	0.06	0.00
Ionising radiation	µPt	0.43	0.04	0.04	0.04	0.08	0.15	0.08	0.02	-0.02
Land use	µPt	2.04	0.32	1.23	0.15	0.16	0.04	0.05	0.10	0.00
Ozone depletion	µPt	0.25	0.00	0.01	0.00	0.04	0.18	0.01	0.01	0.00
Photochemical ozone formation	µPt	2.57	0.21	0.58	0.24	0.91	0.31	0.13	0.20	-0.01
Resource use, fossils	µPt	8.05	1.03	1.34	0.69	2.13	1.94	0.53	0.48	-0.09
Resource use, minerals and metals	µPt	7.38	1.00	0.47	0.29	0.42	4.54	0.33	0.34	0.00
Water use	µPt	4.82	0.15	3.69	0.13	0.32	0.17	0.14	0.23	0.00
Total	**µPt**	**67.65**	**6.91**	**24.37**	**4.87**	**11.92**	**11.12**	**3.21**	**5.21**	**0.04**

Table 13 *Most relevant impact categories and their contribution to the single score, most relevant stages and processes and their contribution to each impact category (where process that have a negative impact score are converted into positive scores)*

Most relevant impact category	[%]	Most relevant life stages	[%]	Most relevant processes	[%]	Most relevant direct elementary flows	[%]	Compartment
Climate change	21.8	Stage 4. Distribution	26.5	Transport, truck >20t, EURO5, 100%LF, default/GLO	17.7			
				Biowaste {RoW}| treatment of biowaste, open dump	2.3			
				Transport, truck <10t, EURO5, 20%LF, default/GLO	0.5			
				Energy, from diesel burned in machinery/RER	0.5			
		Stage 2. Cultivation	22.0	Energy, from diesel burned in machinery/RER	5.3			
				Stage 2. Cultivation green beans {FR}	4.4	Carbon dioxide, land transformation	85.1	Air
				Electricity, low voltage {NL}| market for	2.9			
				Stage 2. Cultivation white mushrooms {NL}	1.8	Dinitrogen monoxide	88.6	Air
				Stage 2. Cultivation cabbages {PL}	1.5	Dinitrogen monoxide	98.4	Air
				Heat from CHP, natural gas {NL}	1.2			
				Stage 2. Cultivation carrots {NL}	1.2	Dinitrogen monoxide	68.9	Air
						Carbon dioxide, land transformation	31.1	Air
				Stage 2b. Cultivation tomatoes {ES}	0.9	Dinitrogen monoxide	100.0	Air
				Stage 2a. Cultivation tomatoes {IT}	0.8	Dinitrogen monoxide	100.0	Air
		Stage 5. Consumer packaging	13.3	Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production, granulate, bottle grade	4.9			
				Extrusion of plastic sheets and thermoforming, inline {RoW}| processing	2.2			
				Electricity, low voltage {RER}| market group for electricity, low voltage	2.2			
				Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene	1.2			

Most relevant impact category	[%]	Most relevant life stages	[%]	Most relevant processes	[%]	Most relevant direct elementary flows	[%]	Compartment
				Transport, truck >20t, EURO5, 80%LF, empty return/GLO	0.6			
				Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate	0.5			
		Stage 1. Raw materials	12.0	Greenhouse tunnel, type Rovero, at processing/GLO	2.7			
				Potassium nitrate {RER}| potassium nitrate production	1.0			
				Calcium ammonium nitrate (CAN), (NPK 26.5-0-0), market mix, at regional storage/RER	1.0			
				Tomato seedling, for planting {IT}| tomato seedling production, in unheated greenhouse, for planting	0.8			
				Electricity, low voltage {NL}| market for	0.8			
				Compost, for mushroom cultivation, at processing {NL}	0.7	Dinitrogen monoxide	51.5	Air
						Methane, biogenic	48.5	Air
				Ammonium nitrate, as 100% $(NH_4)(NO_3)$ (NPK 35-0-0), market mix, at regional storage/RER	0.5			
		Stage 7. Use stage	9.8	Biowaste {RoW}| treatment of biowaste, open dump	3.0			
				Transport, truck >20t, EURO5, 100%LF, default/GLO	1.7			
				Energy, from diesel burned in machinery/RER	0.5			
				Biowaste {RoW}| treatment of biowaste by anaerobic digestion	0.5			
				Electricity, low voltage {PL}| market for electricity, low voltage	0.5			
				Heat, district or industrial, natural gas {RER}| market group for heat, district or industrial, natural gas	0.5			
		Other: Stage 3. Post-harvest treatment, storage and handling		Electricity, low voltage {PL}| market for electricity, low voltage	3.2			
				Transport, tractor and trailer, agricultural {RoW}| market for transport, tractor and trailer, agricultural	2.0			
				Stage 2. Cultivation green beans {FR}	0.9	Carbon dioxide, land transformation	85.1	Air
				Transport, truck >20t, EURO5, 100%LF, default/GLO	0.8			
				Electricity, low voltage {NL}| market for	0.6			
		Other: Stage 8. End-of-life		Waste polyethylene {RoW}| treatment of waste polyethylene, municipal incineration	1.9			
		Other: Stage 6. Retail		Electricity, low voltage {RER}| market group for electricity, low voltage	1.8			
				Biowaste {RoW}| treatment of biowaste, open dump	0.8			
				Electricity, low voltage {NL}| market for	0.5			
				Waste polyethylene {RoW}| treatment of waste polyethylene, municipal incineration	0.5			
				Transport, truck >20t, EURO5, 100%LF, default/GLO	0.5			
Resource use, fossils	11.8	Stage 4. Distribution	26.7	Transport, truck >20t, EURO5, 100%LF, default/GLO	20.1			
				Transport, truck <10t, EURO5, 20%LF, default/GLO	0.6			
		Stage 5. Consumer packaging	24.3	Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production, granulate, bottle grade	9.7			
				Electricity, low voltage {RER}| market group for electricity, low voltage	4.0			
				Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene	2.8			
				Extrusion of plastic sheets and thermoforming, inline {RoW}| processing	2.2			
				Polyethylene, high density, granulate {RER}| polyethylene production, high density, granulate	1.6			
				Transport, truck >20t, EURO5, 80%LF, empty return/GLO	0.7			
		Stage 2. Cultivation	16.0	Energy, from diesel burned in machinery/RER	6.0			

Most relevant impact category	[%]	Most relevant life stages	[%]	Most relevant processes	[%]	Most relevant direct elementary flows	[%]	Compartment
				Heat from CHP, natural gas {NL}	4.9			
				Electricity, low voltage {NL}| market for	3.1			
		Stage 1. Raw materials	12.9	Greenhouse tunnel, type Rovero, at processing/GLO	2.6			
				Black peat DE (updated)	1.4	Energy, from peat	100.0	Raw
				Potassium nitrate {RER}| potassium nitrate production	1.1			
				Calcium ammonium nitrate (CAN), (NPK 26.5-0-0), market mix, at regional storage/RER	1.0			
				Electricity, low voltage {NL}| market for	0.9			
				Tomato seedling, for planting {IT}| tomato seedling production, in unheated greenhouse, for planting	0.8			
		Other: Stage 6. Retail		Electricity, low voltage {RER}| market group for electricity, low voltage	3.4			
				Heat from CHP, natural gas {NL}	0.9			
				Electricity, low voltage {NL}| market for	0.6			
		Other: Stage 3. Post-harvest treatment, storage and handling		Electricity, low voltage {PL}| market for electricity, low voltage	2.9			
				Transport, tractor and trailer, agricultural {RoW}| market for transport, tractor and trailer, agricultural	2.0			
				Transport, truck >20t, EURO5, 100%LF, default/GLO - Stage 3. Post-harvest handling and storage	0.9			
				Electricity, low voltage {NL}| market for	0.7			
		Other: Stage 7. Use stage		Transport, truck >20t, EURO5, 100%LF, default/GLO	2.0			
				Electricity, high voltage {RER}| market group for electricity, high voltage	0.7			
				Electricity, low voltage {RER}| market group for electricity, low voltage	0.7			
				Energy, from diesel burned in machinery/RER	0.6			
				Heat, district or industrial, natural gas {RER}| market group for heat, district or industrial, natural gas	0.6			
		Other: Stage 8. End-of-life		Electricity, high voltage {RER}| market group for electricity, high voltage	0.6			
Resource use, minerals and metals	10.9	Stage 5. Consumer packaging	61.5	Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production, granulate, bottle grade	57.0			
				Electricity, low voltage {RER}| market group for electricity, low voltage	2.3			
		Stage 1. Raw materials	13.5	Phosphoric acid, merchant grade (75% H_3PO_4) (NPK 0-54-0), at plant/RER	4.2			
				NPK compound (NPK 15-15-15), market mix, at regional storage/RER	1.5			
				Triple superphosphate, as 80% $Ca(H_2PO_4)2$ (NPK 0-48-0), at plant/RER	1.5			
		Stage 2. Cultivation	6.3	Energy, from diesel burned in machinery/RER	4.4			
				Electricity, low voltage {NL}| market for	1.7			
		Other: Stage 4. Distribution		Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production, granulate, bottle grade	3.2			
		Other: Stage 7. Use stage		Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production, granulate, bottle grade	2.4			
		Other: Stage 6. Retail		Electricity, low voltage {RER}| market group for electricity, low voltage	2.0			
Acidification	9.2	Stage 2. Cultivation	51.3	Stage 2. Cultivation white mushrooms {NL}	28.4	Ammonia, NL	100.0	Air
				Stage 2. Cultivation carrots {NL}	8.8	Ammonia, NL	100.0	Air
				Energy, from diesel burned in machinery/RER	3.9			
				Stage 2. Cultivation cabbages {PL}	2.9	Ammonia, PL	100.0	Air
				Heat from CHP, natural gas {NL}	2.3			
				Stage 2c. Cultivation tomatoes {NL}	1.5	Ammonia, NL	100.0	Air
				Stage 2. Cultivation green beans {FR}	1.1	Ammonia, FR	100.0	Air
		Stage 4. Distribution	16.6	Transport, truck >20t, EURO5, 100%LF, default/GLO	10.2			
				Stage 2. Cultivation white mushrooms {NL}	2.3	Ammonia, NL	100.0	Air

Most relevant impact category	[%]	Most relevant life stages	[%]	Most relevant processes	[%]	Most relevant direct elementary flows	[%]	Compartment
				Stage 2. Cultivation carrots {NL}	0.7	Ammonia, NL	100.0	Air
		Stage 7. Use stage	8.6	Stage 2. Cultivation white mushrooms {NL}	3.2	Ammonia, NL	100.0	Air
				Stage 2. Cultivation carrots {NL}	1.0	Ammonia, NL	100.0	Air
				Transport, truck >20t, EURO5, 100%LF, default/GLO	1.0			
		Stage 1. Raw materials	7.3	Calcium ammonium nitrate (CAN), (NPK 26.5-0-0), market mix, at regional storage/RER	1.6			
				Greenhouse tunnel, type Rovero, at processing/GLO	1.2			
				Ammonium nitrate, as 100% $(NH_4)(NO_3)$ (NPK 35-0-0), market mix, at regional storage/RER	0.8			
		Other: Stage 3. Post-harvest treatment, storage and handling		Electricity, low voltage {PL}| market for electricity, low voltage	2.3			
				Transport, tractor and trailer, agricultural {RoW}| market for transport, tractor and trailer, agricultural	1.4			
		Other: Stage 5. Consumer packaging		Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production, granulate, bottle grade	2.0			
				Electricity, low voltage {RER}| market group for electricity, low voltage	1.2			
				Extrusion of plastic sheets and thermoforming, inline {RoW}| processing	1.1			
		Other: Stage 6. Retail		Electricity, low voltage {RER}| market group for electricity, low voltage	1.0			
				Stage 2. Cultivation white mushrooms {NL}	0.7	Ammonia, NL	100.0	Air
Particulate matter	9.1	Stage 2. Cultivation	54.4	Stage 2. Cultivation white mushrooms {NL}	18.7	Ammonia, NL	100.0	Air
				Energy, from diesel burned in machinery/RER	7.8			
				Stage 2. Cultivation carrots {NL}	5.8	Ammonia, NL	100.0	Air
				Stage 2b. Cultivation tomatoes {ES}	5.1	Ammonia, ES	100.0	Air
				Stage 2a. Cultivation tomatoes {IT}	4.9	Ammonia, IT	100.0	Air
				Stage 2. Cultivation green beans {FR}	3.6	Ammonia, FR	100.0	Air
				Stage 2. Cultivation cabbages {PL}	3.5	Ammonia, PL	100.0	Air
				Heat, district or industrial, other than natural gas {RER}| heat production, wood chips from post-consumer wood, at furnace 300kW	2.0			
				Stage 2c. Cultivation tomatoes {NL}	1.0	Ammonia, NL	100.0	Air
				Heat from CHP, natural gas {NL}	0.7			
		Stage 4. Distribution	12.6	Transport, truck >20t, EURO5, 100%LF, default/GLO	5.9			
				Stage 2. Cultivation white mushrooms {NL}	1.5	Ammonia, NL	100.0	Air
				Energy, from diesel burned in machinery/RER	0.7			
		Stage 1. Raw materials	9.7	Greenhouse tunnel, type Rovero, at processing/GLO	3.1			
				Calcium ammonium nitrate (CAN), (NPK 26.5-0-0), market mix, at regional storage/RER	1.5			
				Potassium nitrate {RER}| potassium nitrate production	0.8			
				Ammonium nitrate, as 100% $(NH_4)(NO_3)$ (NPK 35-0-0), market mix, at regional storage/RER	0.7			
		Stage 7. Use stage	7.8	Stage 2. Cultivation white mushrooms {NL}	2.1	Ammonia, NL	100.0	Air
				Energy, from diesel burned in machinery/RER	0.8			
				Stage 2. Cultivation carrots {NL}	0.7	Ammonia, NL	100.0	Air
				Stage 2. Cultivation cabbages {PL}	0.7	Ammonia, PL	100.0	Air
				Transport, truck >20t, EURO5, 100%LF, default/GLO	0.6			
		Other: Stage 5. Consumer packaging		Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production, granulate, bottle grade	2.7			
				Extrusion of plastic sheets and thermoforming, inline {RoW}| processing	1.9			
				Packaging film, low density polyethylene {RER}| packaging film production, low density polyethylene	0.6			

Most relevant impact category	[%]	Most relevant life stages	[%]	Most relevant processes	[%]	Most relevant direct elementary flows	[%]	Compartment
				Electricity, low voltage {RER}| market group for electricity, low voltage	0.6			
		Other: Stage 3. Post-harvest treatment, storage and handling		Transport, tractor and trailer, agricultural {RoW}| market for transport, tractor and trailer, agricultural	1.4			
				Stage 2. Cultivation green beans {FR}	0.8	Ammonia, FR	100.0	Air
Water use	7.1	Stage 2. Cultivation	76.5	Stage 2b. Cultivation tomatoes {ES}	43.3	Water, river, ES	100.0	Raw
				Stage 2a. Cultivation tomatoes {IT}	28.2	Water, unspecified natural origin, IT	100.0	Raw
				Stage 2. Cultivation green beans {FR}	3.1	Water, well, FR	100.0	Raw
		Stage 4. Distribution	6.7	Stage 2b. Cultivation tomatoes {ES}	3.5	Water, river, ES	100.0	Raw
		Other: Stage 7. Use stage		Stage 2b. Cultivation tomatoes {ES}	2.5	Water, river, ES	100.0	Raw
Eutrophication, marine	6.2	Stage 2. Cultivation	60.8	Stage 2. Cultivation white mushrooms {NL}	13.6	Nitrate, NL	91.1	Water
				Stage 2. Cultivation cabbages {PL}	12.9	Nitrate, PL	98.2	Water
				Stage 2b. Cultivation tomatoes {ES}	7.6	Nitrate	95.7	Water
				Stage 2. Cultivation carrots {NL}	7.0	Nitrate	94.6	Water
				Stage 2a. Cultivation tomatoes {IT}	6.5	Nitrate	95.1	Water
				Stage 2. Cultivation green beans {FR}	5.7	Nitrate, FR	95.9	Water
				Energy, from diesel burned in machinery/RER	3.2			
				Heat from CHP, natural gas {NL}	2.0			
				Stage 2c. Cultivation tomatoes {NL}	1.3	Nitrate	95.1	Water
		Stage 4. Distribution	15.6	Transport, truck >20t, EURO5, 100%LF, default/GLO	8.6			
				Stage 2. Cultivation cabbages {PL}	1.1	Nitrate, PL	98.2	Water
				Stage 2. Cultivation white mushrooms {NL}	1.1	Nitrate, NL	91.1	Water
				Biowaste {RoW}| treatment of biowaste, open dump	1.0			
		Stage 7. Use stage	9.3	Stage 2. Cultivation cabbages {PL}	2.4	Nitrate, PL	98.2	Water
				Stage 2. Cultivation white mushrooms {NL}	1.5	Nitrate, NL	91.1	Water
				Biowaste {RoW}| treatment of biowaste, open dump	1.3			
		Stage 3. Post-harvest treatment, storage and handling		Stage 2. Cultivation cabbages {PL}	1.6	Nitrate, PL	98.2	Water
				Stage 2. Cultivation green beans {FR}	1.2	Nitrate, FR	95.9	Water
				Transport, tractor and trailer, agricultural {RoW}| market for transport, tractor and trailer, agricultural	1.0			
Eutrophication, freshwater	6.0	Stage 2. Cultivation	46.8	Stage 2. Cultivation white mushrooms {NL}	19.7	Phosphorus	100.0	Soil
				Stage 2. Cultivation green beans {FR}	5.1	Phosphorus	100.0	Soil
				Stage 2b. Cultivation tomatoes {ES}	4.4	Phosphorus	100.0	Soil
				Stage 2a. Cultivation tomatoes {IT}	3.5	Phosphorus	100.0	Soil
				Electricity, low voltage {NL}| market for	3.4			
				Stage 2. Cultivation carrots {NL}	3.1	Phosphorus	100.0	Soil
				Stage 2. Cultivation cabbages {PL}	2.9	Phosphorus	100.0	Soil
				Energy, from diesel burned in machinery/RER	1.1			
		Stage 3. Post-harvest treatment, storage and handling	13.3	Electricity, low voltage {PL}| market for electricity, low voltage	8.8			
				Stage 2. Cultivation green beans {FR}	1.1	Phosphorus	100.0	Soil
				Transport, tractor and trailer, agricultural {RoW}| market for transport, tractor and trailer, agricultural	1.0			
				Electricity, low voltage {NL}| market for	0.7			
		Stage 5. Consumer packaging	11.6	Electricity, low voltage {RER}| market group for electricity, low voltage	4.7			
				Polyethylene terephthalate, granulate, bottle grade {RER}| polyethylene terephthalate production, granulate, bottle grade	2.3			
				Extrusion of plastic sheets and thermoforming, inline {RoW}| processing	2.3			

Most relevant impact category	[%]	Most relevant life stages	[%]	Most relevant processes	[%]	Most relevant direct elementary flows	[%]	Compartment
		Stage 7. Use stage	8.7	Stage 2. Cultivation white mushrooms {NL}	2.2	Phosphorus	100.0	Soil
				Electricity, low voltage {PL}| market for electricity, low voltage	1.4			
				Biowaste {RoW}| treatment of biowaste, open dump	1.0			
				Electricity, high voltage {RER}| market group for electricity, high voltage	0.8			
				Electricity, low voltage {RER}| market group for electricity, low voltage	0.8			
		Other: Stage 6. Retail		Electricity, low voltage {RER}| market group for electricity, low voltage	3.9			
		Other: Stage 1. Raw materials		Greenhouse tunnel, type Rovero, at processing/GLO	2.8			
				Electricity, low voltage {NL}| market for	0.9			
		Other: Stage 4. Distribution		Stage 2. Cultivation white mushrooms {NL}	1.6	Phosphorus	100.0	Soil
				Biowaste {RoW}| treatment of biowaste, open dump	0.8			

7 Interpretation of EF results

7.1 Assessment of the robustness of the EF study

The overall data quality rating (DQR) of this RP study is not assessed in this version of the document.

7.2 Hotspot analysis

The most relevant impact categories, life cycle stages, processes and elementary flows are identified according to the criteria in **Table 14**. There is an important operational difference between most-relevant impact categories and life cycles stages on one hand and most relevant processes, and elementary flows on the other. In particular, most-relevant impact categories and life-cycle stages may be mainly relevant when communicating the results of a PEF study. They might serve to highlight environmental areas where the organisation should focus their attention. Identifying the most-relevant processes and elementary flows is more important for the engineers and designers to identify actions for improving the overall footprint, e.g. by-passing or changing a process, further optimising a process, or applying anti-pollution technology. This is particularly relevant for internal studies, to look deeper into how to improve the product's environmental performance. The hotspot analysis is conducted using aggregated datasets.

Table 14 *Requirements to define most-relevant contributions*

Item	At what level does relevance need to be identified?	Threshold
Most-relevant impact categories	Single overall score	Impact categories that together contribute to at least 80% of the single overall score
Most-relevant life cycle stages	For each most-relevant impact category	All life cycle stages that together contribute more than 80% to that impact category.
Most-relevant processes	For each most-relevant impact category	All processes that together contribute (along the entire life cycle) more than 80% to that impact category, considering absolute values
Most-relevant (direct) elementary flows	For each most-relevant process, considering the most-relevant impact categories	All elementary flows that together contribute to at least 80% of the total impact of a most-relevant impact category for each most-relevant process. If disaggregated data are available: for each most-relevant process, all direct elementary flows that together contribute at least 80% to that impact category (caused by the direct elementary flow).

The most relevant impact categories in this study are (**Figure 4**):

- Climate Change (21.8%);
- Resource use, fossils (11.8%);
- Resource use, mineral and metals (10.9%);
- Acidification (9.2%);
- Particulate matter (9.1%);
- Water use (7.1%);
- Eutrophication, marine (6.2%);
- Eutrophication, freshwater (6.0%).

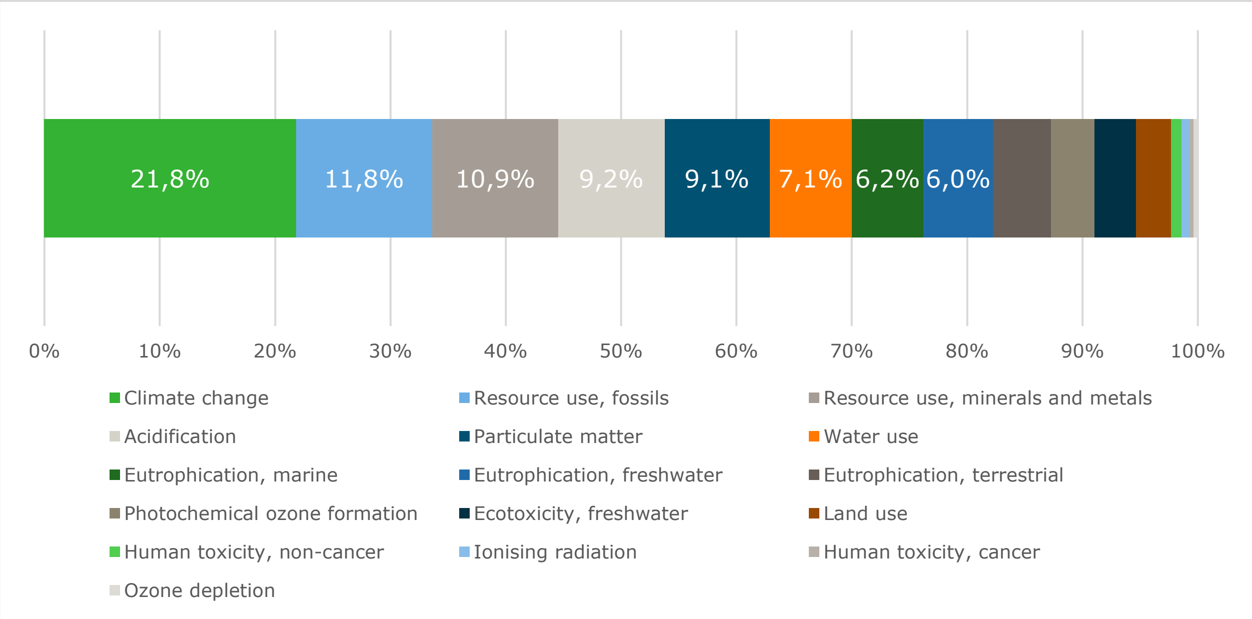

Figure 4 Normalized and weighted impact results sorted from high to low contribution per impact category

The most relevant life cycle stages in this study are (**Figure 5**):

- Stage 1. Raw materials
- Stage 2. Cultivation
- Stage 3. Post-harvest treatment, storage, and handling
- Stage 4. Distribution
- Stage 5. Consumer packaging
- Stage 7. Use stage

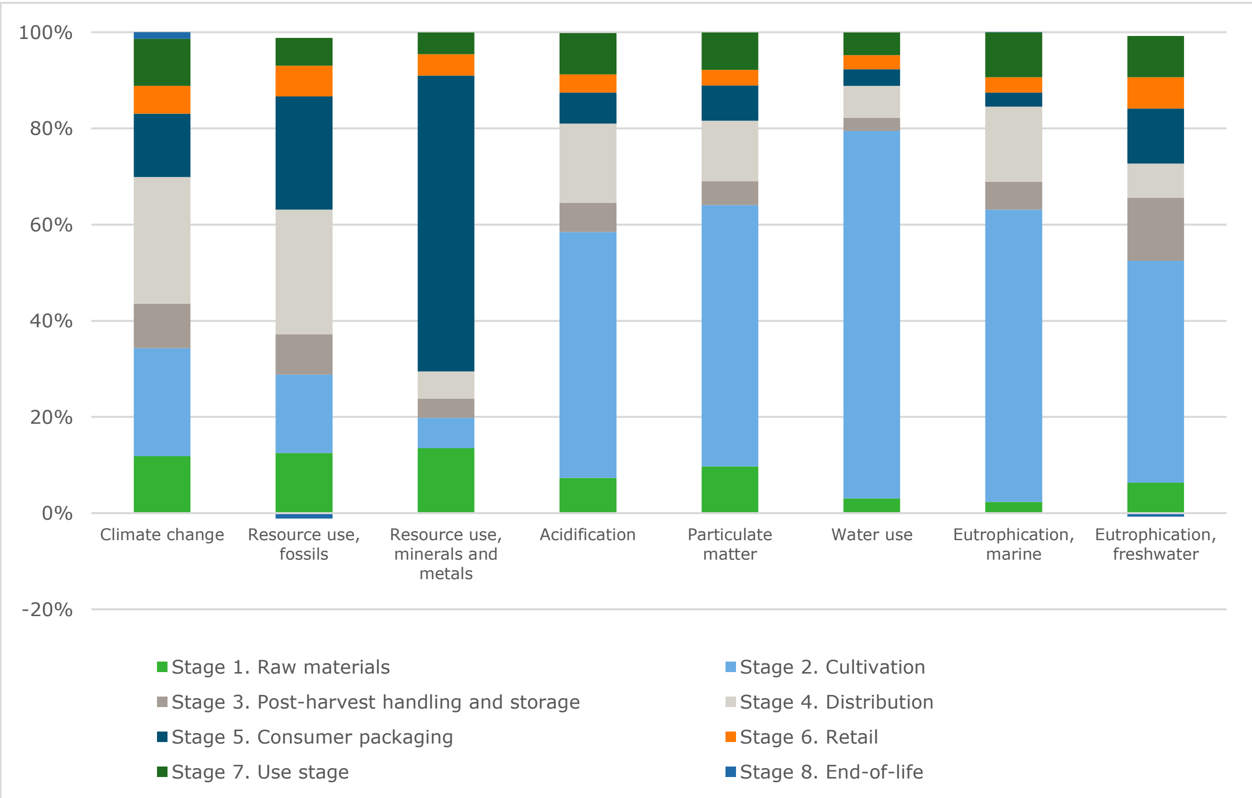

Figure 5 Characterized results for life cycle stages per most-relevant impact category

The complete list of most relevant impact categories, life cycle stages, processes and direct elementary flows can be found in **Table 13**.

7.3 Limitations and relationship of the EF results relative to the defined goal and scope of the EF study

The limitations and relationship of the EF results relative to the defined goal and scope of the PEF study are the following:

- Data quality is not assessed for the overall RP, neither for the individual products the RP is composed of. Therefore, there is no insight in whether the underlying models are equally robust and the overall data quality of the study is sufficient.
- A large variation of data-sources has been consulted and used in the LCA-models underlying to this report. Due to the lack of sufficient data and/or methods, interlinkages between product characteristics and/or management practices (e.g., type of packaging material, food losses, transport modality) are not always reflected accurately.
- The virtual RP does carry the risk that products and technologies with a relative low market share are overlooked, that might have a high environmental impact (e.g., airfreight). This might lead to an underestimation of the total environmental impact of vegetables.
- Plant protection products are modelled per active ingredient. Not all active ingredients are characterized by the EF impact assessment method. This might lead to an underestimation of the impacts for impact categories sensitive to the application of plant protection products (e.g., ecotoxicity).
- The Circular Footprint Formula (CFF) has not been applied at the material input side. Application of the CFF in end-of-life phases also had several shortcomings, e.g. not including actual recycling processes or processes that contain some recycled content (e.g., steel, iron). This is largely due to the lack of interoperability with background datasets.

7.4 Conclusions and recommendations

The following is concluded:

- The most relevant impact categories identified in this study are Climate Change (21.8%); Resource use, fossils (11.8%); Resource use, mineral and metals (10.9%); Acidification (9.2%); Particulate matter (9.1%); Water use (7.1%); Eutrophication, marine (6.2%) and Eutrophication, freshwater (6.0%). These might serve to highlight environmental areas where actors along the vegetable supply chain should focus their attention.
- The most relevant life cycle stages identified in this study are: Stage 1. Raw materials, Stage 2. Cultivation, Stage 3. Post-harvest treatment, storage, and handling, Stage 4. Distribution, Stage 5. Consumer packaging and Stage 7. Use stage. These might serve to highlight environmental areas where actors along the vegetable supply chain should focus their attention.
- Data needs for the product category vegetables have been identified based on this study. Data needs can be found in the 1st draft of the FreshProducePEFCR.
- The Circular Footprint Formula is not fully interoperable with the background databases used in this study.

The following is recommended:

- Nitrogen and Phosphorus emissions were calculated using the default approach from the 1st draft of the FreshProducePEFCR (Weststrate et al, 2024). These emissions contribute to at least four impact categories identified as most relevant, i.e. acidification, particulate matter, eutrophication; marine and eutrophication; freshwater. It is recommended to conduct a sensitivity analysis using the preferred modelling approach as prescribed in the 1st draft of the FreshProducePEFCR.
- Emissions resulting from the use of compost and casing materials are fully attributed to the first user in horticulture, either in the cultivation phase or at transfer at End-of-Life. This implies that neither upstream emissions as well as emissions resulting from the application of the residual product are attributed to the next user. It is recommended to investigate whether this approach reflects reality and/or gives the right incentives to supply chain actors and consumers.
- Conduct supporting studies on products and or technologies that are not well presented in the constructed in the RP (e.g. airfreight, residual heat used in greenhouse cultivation)., but might influence

the conclusions drawn in this study in terms of environmental impact and primary data needs and data collection activities.

- Investigate the usability of the results to be used as a benchmark for the product category vegetables.

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Annexes

Annex 1 List of EF normalization and weighting factors

Table A.1 *Normalisation factors (NF) for Environmental Footprint (EF) 3.1*

Impact categories	Unit	NF
Acidification	mol H^+ eq./person-year	5.56E+01
Climate change	kg CO_2 eq./person-year	7.55E+03
Ecotoxicity, freshwater	CTU_e/person-year	5.67E+04
EF-particulate matter	disease incidences/person-year	5.95E-04
Eutrophication, freshwater	kg P eq./person-year	1.61E+00
Eutrophication, marine	kg N eq./person-year	1.95E+01
Eutrophication, terrestrial	mol N eq./person-year	1.77E+02
Human toxicity, cancer	CTU_h/person-year	1.73E-05
Human toxicity, non-cancer	CTU_h/person-year	1.29E-04
Ionising radiation	kBq U^{235} eq./person-year	4.22E+03
Land use	pt/person-year	8.19E+05
Ozone depletion	kg CFC-11 eq./person-year	5.23E-02
Photochemical ozone formation	kg NMVOC eq./person-year	4.09E+01
Resource depletion, fossils	MJ/person-year	6.50E+04
Resource depletion, minerals and metals	kg Sb eq./person-year	6.36E-02
Water use	m^3 water eq of deprived water/person-year	1.15E+04

Table A.2 *Weighting factors (WF) for Environmental Footprint (EF) 3.1*

Impact categories	WF [%]
Acidification	6.20%
Climate change	21.06%
Ecotoxicity, freshwater	1.92%
EF-particulate matter	8.96%
Eutrophication, freshwater	2.80%
Eutrophication, marine	2.96%
Eutrophication, terrestrial	3.71%
Human toxicity, cancer	2.13%
Human toxicity, non-cancer	1.84%
Ionising radiation	5.01%
Land use	7.94%
Ozone depletion	6.31%
Photochemical ozone formation	4.78%
Resource depletion, fossils	8.32%
Resource depletion, minerals and metals	7.55%
Water use	8.51%

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