

NovIGRain: SUSTAINABLE STORAGE OF GRAINS BY IMPLEMENTING A NOVEL PROTECTANT AND A VERSATILE APPLICATION TECHNOLOGY

D4.7 Report on environmental life cycle assessment NovIGRain

Report on environmental LCA novIGRain	
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ABBREVIATIONS USED

AP	Acidification potential
AR	Assessment report
BM	Biomass
CBA	Cost-Benefit Analysis
CC	Climate change
CF	Characterisation factor
CFP	Carbon footprint
DM	Dry matter
Dual	Dual application (scenario with adulticide and IGR)
EF	Emission factor
eTox	Ecotoxicity of the freshwater environment
EUfw	Eutrophication of the freshwater environment
EUm	Eutrophication of the marine environment
EUt	Eutrophication of the terrestrial environment
FU	Functional unit
FUM	Fumigation (scenario with phosphine)
GHG	Greenhouse gas
GWP	Global warming potential
IGR	Insect Growth Regulator
IPCC	Intergovernmental Panel on Climate Change
IR	Ionising radiation
KO6	K-Obiol ULV 6 (scenario with deltamethrin)
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land use
MG30	Methograin IGR ULV 30 (scenario with s-methoprene)
OD	Ozone depletion
PG50	Pirigrain 50 (scenario with pirimiphos-methyl)
PM	Particulate matter formation
POF	Photochemical ozone formation
RDf	Fossil energy resource depletion
RDm	Mineral resource depletion (minerals, metals)
sLCA	social Life Cycle Assessment
ULV	Ultra-Low Volume (pesticide application)
WU	Depletion of water resources

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1 INTRODUCTION

1.1 Why environmental sustainability assessment is needed for grain storage

The European Union has prioritized the enhancement of grain storage capacity for cereals, oilseeds, and protein crops to improve food security and supply chain resilience. However, storage infrastructure alone is not sufficient to secure grain availability and cannot fully address the broader sustainability challenges in grain management. Both environmental, economic and social dimensions of grain storage practices are increasingly recognized as critical to long-term viability. Beyond capacity, the quality of grain storage has emerged as a key factor in ensuring supply stability and reducing post-harvest losses. Storage losses not only lead to a direct economic impact through reduced marketable volumes, but also degrade grain quality, affecting food and feed value, and in some cases, compliance with food safety standards. Inherently, the post-harvest grain losses, often caused by pest infestations and suboptimal handling, have also environmental costs and social consequences. On the one hand, the gradual phase-out of several chemical pesticides under EU regulation has created demand for safer, socially responsible pest control alternatives. This growing regulatory pressure and resistance trend underscore the urgency for new, sustainable grain protection solutions. On the other hand, the traditional treatment strategies, currently still applied, such as fumigation (eq. aluminium phosphide) and use of liquid contact insecticides (e.g., deltamethrin or pirimiphos-methyl) come with trade-offs in terms of cost, efficacy and environmental and human safety. Furthermore, most of these tools are single-mode solutions, making them increasingly vulnerable to pest resistance when used alone or repeatedly.

The **NovIGRain project** addresses these challenges by developing a novel, integrated grain protection approach. It focuses on two core innovations:

1. An insect growth regulator (IGR) larvicide based on S-methoprene, i.e. Methograin IGR ULV 30 which targets early insect development stages;
2. An ultra-low volume (ULV) application technology that enables more precise and efficient treatment of the larvicide, whether or not combined with an adulticide as a dual application.

This **deliverable** focuses on an environmental Life Cycle Assessment (LCA) of the NovIGRain innovations, particularly Methograin IGR ULV 30 and its application technology, in comparison to current grain storage treatment strategies. The findings aim to support more informed and responsible decisions around the design, deployment, and broader adoption of grain protection technologies that are not only effective and safe but also environmentally sound.

Life cycle assessment (LCA) is used to calculate and evaluate the environmental sustainability of the insecticide production and application, considering its effectiveness compared to currently used alternatives. This method is ISO standardised (ISO, 2006a, 2006b) and meets the necessary quality requirements. The LCA approach is described in detail **in Annex 1**. LCA identifies opportunities to improve environmental performance at different phases of the product life cycle. It can be used to inform decision-makers in government, industry and non-governmental organisations. A full 'cradle-to-grave' assessment would consider all life cycle stages of the grain, from raw material extraction, processing and distribution to end-of-life. The current LCA study is a 'cradle-to-gate' assessment of the environmental impacts up until the grain storage gate. Further stages comprising transport to distributors and/or mills, post-processing, the use and its disposal were excluded from the study. Each LCA study consists of:

1. **Goal and scope (G&S)** definition, which states the intended goal, system boundaries (what to include/exclude) and functional unit(s) among others;
2. **Life cycle inventory (LCI)**, which quantifies all inputs and outputs (resources, energy, emissions, waste) of the system processes through data collection and/or modelling of specific foreground processes and through data from specific LCA databases (e.g. ecoinvent) that contain data for background processes;

3. **Life cycle impact assessment (LCIA)**, which translates the inventory into environmental impact (midpoint) categories and (optionally) into an aggregated single score (with higher uncertainty) through normalisation and weighing;
4. **Life cycle evaluation to interpret the LCI and/or LCIA** results in relation to the goal and scope. This can further include identification of significant issues, sensitivity analysis, conclusions, limitations of the study and recommendations.

Each LCA in this report will present an overview of its specific methodological choices.

1.2 Environmental sustainability assessment: EF and PEF method

There are different methods that can be used to calculate the environmental impact of a product or process. This study uses the environmental footprint (EF) methodology (EC, 2022) established by the European Commission. The EC has put forward the EF method to harmonise product and organisational footprints across Europe in the product environmental footprint (PEF; EC, 2018) and organisational environmental footprint (OEF), respectively. This study applies the EF method to report the environmental sustainability halfway through the cause-effect chain (midpoint) through 16 impact categories (ICs) aggregated into a single score. The single score is a starting point to evaluate which ICs are most relevant for the production system of interest and will be further addressed in more detail (the cut-off criterion to include ICs in more detail is set by the EC at 80% of the total single score). The single score expressed in points (Pt) is a measure of the overall environmental impact of a product and aggregates all 16 individual ICs through normalisation and weighing. Normalisation standardises the impact to the average annual impact of a European civilian for each IC. Weighing is based on EU experts and evidence-based criteria, prioritising environmental themes. The individual impact categories contributing to 80% of the single score, are climate change (21%), particulate matter (9%), water use (9%), fossil resource use (8%), land use (8%), use of mineral resources (8%), ozone depletion (6%), acidification (6%) and ionising radiation (5%). The other 20% is related to ecotoxicity, human toxicity, eutrophication and photochemical ozone formation. **Annex 2** describes all 16 ICs. **Annex 3** lists the normalisation and weighting factors per IC to calculate the single score impact according to the EF 3.1 method. An extensive glossary related to life cycle assessment is provided in **Annex 4**.

1.3 Point of attention

The current LCA study aims to provide insight into and awareness of the environmental impacts of the assessed grain storage strategies and potential measures, rather than to provide absolute impact values. There are several reasons why the calculated impacts should not be regarded as exact or definite: confidentiality issues, data gaps due to lack of specific onsite monitoring, theoretical upscaling, evolving technologies, literature and partner expertise clearly revealing broad ranges of data regarding potential losses in grain quantity and quality depending on the scale, regional practices and seasonal conditions amongst others.

2 Life cycle assessment of grain storage

The LCA study builds on the the NovIGRain project deliverables. Croes & Bamelis (2021) defined the reference scenarios and selected alternatives per region and storage type, providing the structure for a comparative analysis of grain storage treatment strategies. Izinovations et al. (2024) and Szilagyi et al. (2021) offer insight into current commonly used practices, provide grain trade statistics and insecticides usage across the target regions in Europe. As these form the foundation for the parallel studies of the cost-benefit analysis (CBA; Moshkin *et al*. (2025) D4.9) and social life cycle assessment (sLCA; Moshkin *et al*. (2025) D4.8), the LCA is aligned with both studies in a common analytical framework. However, full one-to-one correspondence is neither assumed nor required, as the LCA is adapted in order to reflect the best insight and relevance regarding the environmental impact of grain protection strategies. Based on the internal knowledge base, project deliverables, partners expertise and complementary literature, the assessment aims to reflect the operational realities of grain storage and the potential impact of current protection strategies and to what extent the NovIGRain approach could offer a better environmental performance.

Hence, this LCA aims to identify environmental hotspots and guide future improvements towards ~~a~~ sustainable grain storage.

2.1 Goal and scope

The main objective of this report is to carry out a comparative environmental Life Cycle Assessment (LCA) of grain storage treatments with a special focus on the NovIGRain approach, i.e. the Methograin IGR ULV 30 (MG30) production and its application technology, especially with a dual application with an adulticide.

The assessment therefore focuses on

- A hotspot analysis of the impact along the supply chain, and of the grain treatment in detail, comparing the current existing protection methods and the NovIGRain approach;
- Scenario assessments to address the most relevant parameters subject to lack of (accurate) data, variability and the assumptions made.

To meet the objectives of this study and to assess the environmental risks and opportunities associated with the production and use of a protection product, the assessment in first instance encompasses all critical stages of the grain supply, including grain cultivation and transport and the actual grain storage and specific treatment. The LCA entails an **attributional cradle-to-storage gate assessment** that accounts for all infrastructure, equipment, resources, energy and corresponding emissions for each stage up to the point where grain exits the storage, ready for further processing and consumption.

The supply chain stages and **system boundaries** are shown in **Figure 1** and include grain cultivation, grain transport, grain storage default operations (infrastructure and energy) and more specifically grain treatment including insecticide production and application. Both, background as potential foreground emissions, as well as grain losses are taken into account depending on the storage strategy.

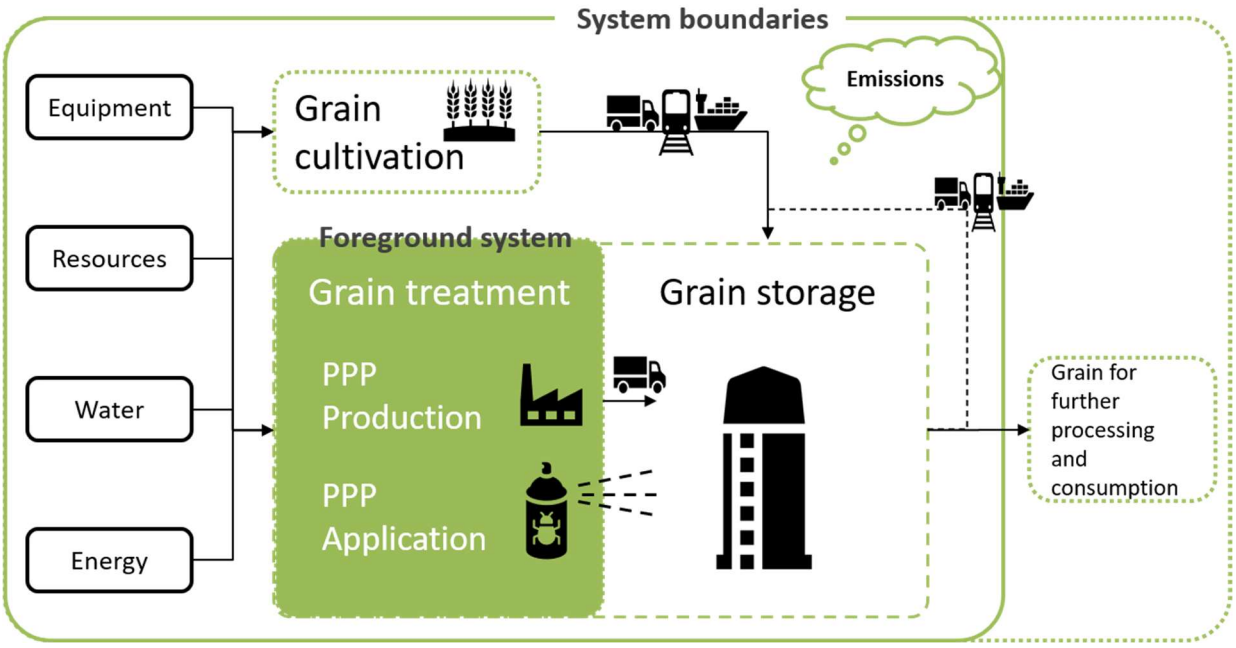


Figure 1. System boundaries (**solid frame**) of the grain supply chain including grain cultivation, transport and storage. Grain storage is the foreground system (**dashed line**), studied in most detail, and entails infrastructure, default operation, and the plant protection product (PPP) production and application with corresponding emissions. Further transport and processing (**dotted line**) of the grain to the final consumer are excluded.

2.1.1 Grain cultivation

Grain **cultivation** typically involves soil management (diesel use), seedling production, irrigation, fertiliser and pesticide application, all of which cause foreground field emissions that include potential toxic compound emissions, greenhouse gases and/or nutrient flows to air, soil and aquatic systems. These emissions in turn contribute to environmental damage as a result of ecosystem and human toxicity, climate change, acidification and eutrophication, among others. The harvested yield – besides the management intensity- determines the final impact at product level. Given the main objective of comparing storage strategies, the cultivation is included but approached by a background process retrieved from a specialised LCA database with default corresponding impact.

2.1.2 Grain transport

The supply chain system includes grain **transport**, in the first place between the cultivation field and the storage facility. Depending on the region and scale of trade, it consists of different transport modes, by truck, train and/or barge, for which the vehicles themselves, diesel and/or electricity production and combustion and a share of the transport network facilities are all included in the assessment. Alternative flows, transporting grain between different facilities, nor the final mode of transport to the processing and consumption stage were considered, due to the high variability of how grain is distributed, especially downstream.

2.1.3 Grain storage

Default **storage operations** include handling, aeration, pest control, and associated energy and material inputs and corresponding emissions. The storage facilities mainly consist either of horizontal concrete based flat storage, or common silos from steel or concrete depending on the scale and trade. The grain is considered to be (un)loaded through mainly electricity driven conveyor belts depending on the capacity. Furthermore, ventilation or aeration is considered as default operation for temperature, moisture and pest control. This basic requirement includes electricity powered auxiliary equipment at the infrastructure. In addition, facilities are cleaned and potentially disinfected before each storage cycle, which requires machinery, water, disinfectant and energy.

*2.1.4 **Grain treatment***

In line with the **treatment strategies** outlined in Croes and Bamelis (2021), and as addressed in the economic impact novIGRain report (Moshkin *et al*. (2025) D4.9), this report focuses on a selected group of grain protection methods that reflect both current practices within the EU and relevant alternatives outside of EU. These treatment strategies were identified based on their prevalence across storage scales, practical relevance, and regulatory or market significance.

The LCA includes both the manufacturing and formulation of the plant protection products as well as its application at the storage facility.

In a chemical plant, the **synthesis** of the active ingredient (e.g. aluminium phosphide, deltamethrin, pririmiphos-methyl or s-methoprene), mainly involves raw materials, water and energy, after which it is formulated with (co-)solvents (e.g. (aromatic) hydrocarbons or naphtha fractions), emulsifiers (e.g. alkylbenzene sulfonates as anionic surfactant), stabilisers (e.g. butylated hydroxytoluene (BHT) as phenolic antioxidants), other additives (e.g. piperonyl butoxide (PBO) as synergist or ammonium carbamate as gas modifier) and carriers (e.g. clay, water or oils/esters). Next, their packaging and distribution is taken into account.

Once at the storage facility, their **application** includes equipment (e.g. sprayers), energy and potential emissions of the active ingredient. In general, unless otherwise stated, air emissions are usually considered negligible in regulatory risk assessments, and therefore as well in LCA studies, due to a low vapour pressure, low Henry's law constant, strong adsorption to, i.c. grain and the rationale that most approved storage insecticides are indeed designed to remain bound. Therefore, following strict application protocols, exposure is often not considered relevant regarding human or eco-toxicity impacts, although the rates of AI release depend on storage conditions, leakage, chemical reactions, adsorption and degradation. The selected treatments for this assessment entail a dosage for 12 months of protection.

More specifically the assessment covers (as outlined in Moshkin *et al*. (2025) D4.9):

- **Fumigation**

Among the most widely used approaches is fumigation, typically involving phosphine gas. Fumigation remains a cornerstone of grain storage protection due to its broad-spectrum efficacy and ability to control multiple insect life stages. However, it presents significant limitations, including safety risks to operators, strict application protocols, increasing resistance, and a narrowing regulatory pathway within the EU (Machuca-Mesa et al., 2024; Verwilghen, 2022).

Phostoxin tablets, often manually applied under strict safety measures and based on aluminium phosphide (and ammonium carbamate) release phosphine gas when it reacts with moisture. A high proportion of phosphine ultimately dissipates into air once the fumigation period is over when opening the storage facility to vent. Also reaction products ammonia (NH_3) and carbon dioxide (CO_2) are specifically considered as they are emitted from the ammonium carbamate.

- **Common liquid insecticides**

Another prevalent strategy is the use of liquid insecticides, in particular products based on deltamethrin and pirimiphos-methyl. These are applied either directly to grain or to storage infrastructure and provide residual protection, primarily against adult insects. Their relative affordability and ease of use have made them common at both mid-to-large-scale storage sites and at the farm level. However, their future use is challenged by emerging resistance and a tightening EU regulatory framework concerning active substances (Verwilghen, 2022). Liquid insecticides applied directly to grain during storage are a core element of pest management strategies in many regions. The products differ significantly in their active substances, application technologies, regulatory status, and target pest stages. These factors directly affect their cost-efficiency, operational feasibility, and appropriateness for different storage settings.

Pirigrain 50 (Pirimiphos-methyl) as K-Obiol ULV6 (deltamethrin) are lower concentration formulation designed for cold nebulisation and ultra-low volume application equipment. Both are typically applied once per storage cycle, with efficacy lasting between 6 to 12 months depending on the dosage. Their main action targets adult

insects, with no residual effect on larvae. Best practice involves application at the top of a grain elevator or conveyor belt where the grains fall into storage. Both active ingredients have a low tendency to volatilise and strong adsorption

- **Insect growth regulators**

In addition to these conventional treatments, the analysis also includes the alternative or complementary protection method, not yet used in the EU, based on S-methoprene, an insect growth regulator. The active substance is recognised for its novel modes of action and favourable toxicological profile, making it potentially valuable in resistance management and low-residue production systems. While not yet commercially available in the EU, products based on S-methoprene are included in the analysis as benchmarks of the potential value of these products.

Methograin IGR 30 ULV represents a prototype under development (NovIGRain project), featuring S-methoprene as the active ingredient. It targets the larval stages of insects and is intended for ULV application. As the product is still in the developmental stage, performance characteristics are yet to be determined. However, for the purposes of analysis, it is benchmarked against the other treatment options to estimate its potential competitiveness. Products targeting larvae to be effective, need uninfested grain, but may offer longer-term protection and reduce the likelihood of reinfestation, particularly in extended storage settings.

- **novIGRain - Dual application**

Ultimately, a combined approach is considered using both the larvicide Methograin IGR ULV 30 as liquid adulticide, i.c. the K-Obiol ULV6. Again, as the product is still in the development stage, final performance characteristics are yet to be determined. However, for the purposes of analysis, it is benchmarked against the other treatment options to estimate its potential competitiveness.

*2.1.5 **Grain losses & Functional unit***

Despite the grain protection strategies, there is still a probability that the treatment does not perform as intended and post-harvest **grain losses** occur during storage caused by a.o. pest infestations. Aligned with the CBA study (Moshkin *et al*. (2025) D4.9), a probability of failure serves as a baseline to distinct the fraction of grain fulfilling milling grade grain for human consumption standards, and the remaining downgraded fraction which suffers from quantitative and qualitative losses, but still might serve a function depending on the severity of quality loss. These factors determine the functionality of the system. The assessment outcome ultimately relates to this functional unit comparing the impact of the different protection strategies.

2.1.5.1 Probability of failure

NovIGRain's partner team from Czech Agrifood Research Centre (CARC) derived these probabilities based on an extensive review of literature on protectant efficacy, focusing on species-specific performance and environmental factors (performed by UE, more details in Moshkin *et al*. (2025) D4.9). The scoring approach considers:

- Observed efficacy ranges for key insect species under typical storage conditions for analysed regions and storage scales.
- Variability due to temperature, season, exposure time, and resistance status.
- Treatment type (e.g., pyrethroid vs. organophosphate) and whether combined strategies were used

Over all regions, scales and trade, the ranges of risks per treatment strategy represent the best possible estimate of their variable performance, based on the available information, reflecting both biological uncertainty and operational realities.

2.1.5.2 Quantitative & qualitative losses:

A combination of factors, including mould and mycotoxin development, poor handling practices and pest infestations, result into grain losses in terms of quantity (i.e. reduction in volume) and/or quality (i.e. safe

nutritional deterioration). As outlined in the economic assessment (Moshkin *et al.* (2025) D4.9) and implemented in the social assessment (Moshkin *et al.* (2025) D4.8), **quantitative grain losses** is difficult to determine due to variability in pest pressure, storage duration, environmental conditions, and the quality of initial post-harvest handling. Losses can also be highly localised and fluctuate significantly from year to year. Based on feedback gathered during consortium meetings and individual interviews, quantitative loss appears to play a smaller role in the grain trade. Yet, the assessment accounts for a potential, quantitative loss of the degraded fractions of grain.

Qualitative losses, often the consequence of pests identified in storage, compared to quantitative losses are often more critical, yet hard to quantify by a single measure. Besides, infested grain does not automatically downgrade its function as it is also often a matter of value loss due to negotiations, logistics, market demands etc. The presence of moulds, contaminants and/or (fragments of) insects affect the safety, compositional or nutritional value and functionality. The type and degree of deterioration determines the valorisation of downgraded grain as feed or energy source, not necessarily in a cascade decline, but depending on the type of grain, type of pest and infestation level, until the grain has suffered too much damage and is considered as waste without any function or value. In this study, as it is not the main scope and is assumed the same over all treatments, potential quality loss is approximated by an aggregated reduction in functional value integrating mainly compositional/energetic degradation (macronutrient rebalancing caused by selective consumption of either starch or protein targeted by insects; it drives gross energy content), digestibility loss (reduced accessibility for animals; captured by metabolisable energy) and contamination load (dockage, insect fragments, mycotoxins; also limits feed valorisation). For all treatments, a as default assessment, a fixed functional degradation is considered as baseline, but the higher the damage, the higher the quality loss, differentiating the safe milling-grade grain more from the downgraded grain.

Recognised by ISO 14044 allocation hierarchy avoiding allocation, and analogue to LCA studies using f.i. protein-quality -corrected functional units for comparing foods (Dominguez-Aldama *et al.* (2023)*)*, this assessment implements a 'storage-loss analogue, folding in a correction factor into the denominator, i.e. the functional unit. In order to compare grain treatment strategies capturing the performance of the grain conservation and taking into account the changeable functionality of downgraded grain, **a quantity and quality adapted functional unit** was implemented to integrate food grade grain and functionally downgraded grain fractions avoiding allocation over potentially multiple grades of quality grain products.

Therefore, in this study, the FU was defined as 1 tonne of adjusted grain-equivalent in terms of functional degradation from harvested grain, further referred to as 'functional grain', where the downgraded grain fraction is corrected by a retaining quantity and quality factor, entailing a potential physical weight loss on the one hand and a functional degradation on the other hand which determines a potential pathway as either (most commonly) feed, biofuel and/or for energy recuperation, up till the point it could considered a waste product. This is represented by following formulas:

$$M_{eff} = M * [(1 - dg) + dg * qt * ql] \qquad (1)$$

$$Impact\ per\ tonne\ of\ grain\ =\ total\ inputs\ /\ Meff \qquad (2)$$

With M, Meff: amount of grain incoming into storage and effectively obtained after storage
dg: downgraded fraction (-) based on the probability of failure
qt: retained grain quantity
ql: retained grain quality

Hereby, the functional unit reflects a retained functional performance relative to food-grade grain, as it still serves a function. The price, acceptability or market grade are merely consequences in this LCA context, reflecting different logics.

Further downstream stages of the grain, i.e. final grain transport and processing at any mill, processor or consumer, is excluded from the assessment, given the variability of processing and distribution options in practice. Although these handling practices do not affect the upstream functionality of grain storage nor a fair and relevant comparison regarding the environment performance of different grain treatment strategies, it can be argued that the system boundaries should be extended to include these pathways as active substance residues on the grain differ between the scenario's and where they end up. Risk assessments do address residues of parent compounds and relevant toxic metabolites on the grain and processed product regarding food safety standards. Applied dosage rates at storage are limited as Maximum Residue Levels (MRL) cannot be exceeded for consumer safety, and entail conservative toxicological and exposure assessments. Furthermore, processing matters as residues concentrate on the bran, which often leads to non-detectable residues on food products in practice. Although focused on plant protection product application on the field, the OLCA-Pest platform (Nemecek *et al.,* 2022) addresses the scientific gap and priorities in ongoing and for further research on improving the modelling of pesticide secondary emissions, further extending emission modelling (e.g. additional application techniques, including cover crops), considering metal-based pesticides in emission models, and systematically assessing human health impacts associated with pesticide residues in food crops. As USEtox factors (used for conversion in the toxicity impact categories) do not explicitly model food ingestion pathways and exposure logic (acute vs chronic), digestion kinetics, bioavailability differences and residue variability would be ignored, it goes beyond the scope of this study to account for the post-storage residue implications. Given the complexity and overall lack of robust background modelling and data, especially regarding post-harvest stage of storage, the LCA outcome therefore will be evaluated given the current system boundaries up until the storage exit gate.

Regarding the life cycle inventory stage of the assessment, f**oreground** data, related to the insecticide production and application, were based on partner input and/or theoretical modelling, published literature and expert communication. The ecoinvent 3.10 database was used for **background** data related to the corresponding input material and energy resources. It should be noted that the assessment overall was approached through a hybrid model, based on the data and experimental findings of project partners Babolna and Sojam and personal communication with experts, only reported in the study to a certain extent due to confidentiality**.** It was supplemented by estimations and assumptions to gap fill and extrapolate in order to perform a relevant comparison of the different storage protection strategies.

The environmental impact assessment (LCIA) was quantified using the EF 3.1 **method** and EF 3.1 normalisation and weighting set. The methodology reports the impact at midpoint for 16 ICs, and an aggregated single score combining all impacts.

2.2 Life Cycle Inventory

This step lists and quantifies all input and output flows, including emissions and waste treatments if applicable, within the system boundaries as determined. It comprises data collection related to the grain cultivation, transport, storage operations, treatment and potential losses. The assessment aimed to be as complete and accurate as possible including all relevant practices of the full system, but certain proxies in the LCA database were used and data gaps were filled or excluded as a function of data availability, implemented guidelines and other scientific studies.

An overview of the relevant inventory of all input data considered for the assessment is provided in

Table *1* regarding the relevant parameters applied and more detailed for grain treatment per protection strategy in **Error! Reference source not found.** all expressed per tonne of grain (unless specified otherwise). Overall, except for the grain treatment and losses, main resources, equipment and energy requirements are similar for all treatment scenarios due to the generic approach to represent a European grain supply chain.

*2.2.1 **Grain cultivation,***

Given the focus on grain storage, the **cultivation** stage is taken from the background LCA database which entail average practices and corresponding yields for European countries, resulting in an environmental impact due to a.o. fertilization and inherent field emissions (mainly greenhouse gas N_2O) once applied, diesel fuelled field operations, electricity or diesel driven irrigation and broad pesticide applications at a rate of 1.2 to 2.4 kgAI/t of which by default 9% is emitted to air, 1% to the aquatic environment and 90% to soil (PEFCR (EC, 2018)).

*2.2.2 **Grain transport***

Grain transport numbers, from field to storage facilities across Europe, were extracted from the baseline grain transport routes outlined in the social LCA report (Moshkin *et al*. (2025) D4.8) covering the different regions and scale of trade, obtaining a weighted average value for the distance per mode of transport (truck, train and barge) implemented for the default supply chain LCA to evaluate its relative contribution.

*2.2.3 **Grain storage operations***

Regarding the **infrastructure**, an extrapolation of a long term storage facility from a background database was made, which is composed of 5 steel or concrete units with a capacity of 4000 t each, with a turnover of 1.2 and lifetime of 30 years, which covers the facilities' construction and land occupation.

Generic data for the (un)**loading** of the grain in/out storage, **ventilation** and **cleaning** of the storage was extracted as well from the background databases, addressing equipment, but mainly energy use for either reception and silaging of grain, ventilation systems and cleaning, obtaining generic consumption rates. Overall, the storage operations cover the main energy use of 2.2 kWh per tonne grain stored, as pesticide application is relatively negligible. An average European electricity mix was considered as background process regarding the impact. Regarding cleaning, a treatment by K-Obiol EC25 was assumed applying 40mL of product for 75 m^2 surface area. The assessment includes resulting emissions of the deltamethrin, similar to the grain treatment as addressed in the next paragraph 2.2.4.

Table 1. Life cycle inventory parameters of the grain supply chain.

	Inputs per tonne (unless stated otherwise)
Grain cultivation	
Cultivation	• (In)organic fertilisation: 120 - 440 kgN/ha or 20 - 50kgN/t • Plant Protection Product application: 1.2 - 2.4 kg AI/ha or **0.2 - 0.5 kgAI/t** • Diesel use: 90 - 120 L / ha • Irrigation: 0 – 100 m^3/t • Yield: 4 - 9 t/ha (excl. straw)
Grain transport	
Truck	70 tkm (20 – 250)
Train	180 tkm (0 – 1200)
Barge	100 tkm (0 - 650)
Grain storage	
Infrastructure	0.2kg steel or 0.003m^3 reinforced concrete, given a 30y lifetime and a long term turnover of 1.2
Default operations	• (un)loading: 0.001 m conveyor belt & 0.75 kWh • Ventilation: 1e-5 ventilation unit & 1.4 kWh • Cleaning/disinfecting: 0.48 m^2 surface area & 0.03L water & 0.03kWh & 0.5 mL/m^2 K-Obiol EC25
Grain treatment	
PPP production	#Active ingredient (raw materials, water & energy) & inert material: (co-)solvents & emulsifiers & additives & carriers ➔ see table 2 Packaging: 1.16 kg polyethylene plastic (PE) / 20L container or 0.002 kg PE / kg product Distribution: 825 tkm by truck (150 – 1500 tkm)
PPP application	(Dual) application setup: PE pipes, steel pumps, pipes and valves Electricity: (2x) 0.0014 kWh (0.0003-0.015 kWh depending on conveyor rate (20-900 t/h) Emissions: see table 2
Grain loss	
Probability of failure	3-100% (see table 2)
Quantity loss	3% (1-7%), i.e. 97% retained grain.
Quality loss	20% (0-100%), i.e. 80% retained functional quality grain.

*2.2.4 **Grain treatment:***

The LCI of grain treatment includes both the manufacturing and formulation of the plant protection products as well as its application at the storage facility.

Data for the common **products' manufacturing** and formulation (i.e. fumigation and liquid insecticides), were based on the flows of the chemical family the active ingredients belong to as available in the databases. The inventories included the production of the active ingredients (i.c. pyrethroid and organophosphorus compounds) only accounting for the raw materials, processing energy and chemical plant infrastructure. These were then supplemented by the required inert materials (i.e. (co-)solvents, emulsifiers, stabilisers, other additives and carriers) according to the compositional info in the safety data sheets (SDS) of the considered products.

For the formulation of Methograin IGR ULV 30, the data for s-methoprene manufacturing was provided by the manufacturing NovIGRain partner Babolna, yet still at a generic level of material and energy flows due to sensitive information, and thus approximated by common raw materials. Furthermore, similar to KO6, a generic biodiesel or Fatty Acid Methyl Esters (FAME) flow was used as carrier for the Ultra-Low Volume (ULV) application.

Packaging involves generic data flow on default plastic use per L liquid or kg solid pesticide in general, taken from the database. Ultimately, **distribution** of the product from the Hungarian production site to distributors range from 150 to 1500 km, as set in the sLCA report (Moshkin *et al*. (2025) D4.8).

Regarding the **application** of the pesticide products, the equipment, energy use and storage emissions are inventoried. Based on NovIGRain partner Sojam communication and data transfer, the necessary equipment for ULV application, and liquid insecticides sprayers in general, was estimated, while the required application energy was linked to the conveyor rate, i.e. grain handling speed, which can range from 20 t/h at farm, up to 125 and even 900 t/h at trader and port facilities as default values. Overall, its energy use is limited compared to that of the previously mentioned default store operations.

Air emissions from plant protection products applied to stored grain are assessed within the EU pesticide risk assessment framework using EFSA's FOCUS 'Pesticides in Air' guidance (SANCO/10553/2006), and addressed in Draft Assessment Reports (DAR). Yet, specific volatilisation quantities are usually not provided due to their often negligible volatilisation (excl. fumigation) and irrelevant exposure pathways. Nevertheless, they do imply that potential losses depend on the vapour pressure, Henry's law constant and strong sorption capacity of the active ingredients to the grain (https://www.ecfr.gov/current/title-40/chapter-I/subchapter-R/part-796/subpart-B/section-796.1950).

For the purpose of comparing the strategies with different types of compounds, these parameters were used to assume default fractions which reflect in increasing order the volatilisation of deltamethrin (0.0005%) as almost non-volatile, s-methoprene (0,005%) as very low volatile and pirimiphos-methyl (0,5%) as low-moderate compared to phosphine (70%) as gaseous fumigant. The latter is considered not entirely released to cover for incomplete reaction from aluminium phosphide, degradation and sorption a.o.

*2.2.5 **Grain losses***

Grain losses are inventoried by estimating in first place and most importantly the amount of grain not fit for food through the probability of failure of the strategy and subsequently both quantitative and qualitative losses of degraded grain, of which the remaining part still serves as feed, biofuel or other energy source.

2.2.5.1 Probability of failure

As outlined in Section 2.2.5.12.1.5.1, **probabilities of failure** were determined using expert opinions supported by an extensive literature review and the practical experience of the CARC team from resistance studies. It is important to note that these figures represent the best possible estimates based on the available information, but they are not definitive. If additional factors and data were incorporated, the values could differ, and this should be considered when interpreting the analysis presented in this report.

Compared to the economic assessment (Moshkin *et al*. (2025) D4.9), these estimations were used to determine the ranges over all regions and scales of trade, which were overall similar for each treatment and served as defaults for the current assessment, with a few adjustments.

A scenario without treatment (NoT) is expected to show zero expected avoided loss across all storage levels and countries, reflecting the absence of any protective effect against the risk of downgrade. Yet, reflecting optimal conditions regarding weather, optimal management and zero initial infestation pressure, a conventional 20% sensitivity range was assumed. Furthermore, this would underline the potential impact or benefit of the actual treatments under those conditions. The probability of failure for fumigation treatments was per default assumed to be valid for two applications carried out over the 12 months of storage, as at trader level (at farm rather three or four times is common, while only once at ports). The values account for the possibility that some grain entering storage may already be infested but not detected. As a result, the standalone larvicide treatment (MG30) shows much higher failure probabilities (75%) across all scenarios than if the grain is uninfested (5%).

2.2.5.2 Quantitative & qualitative losses

As assessed in the social assessment, based on the feedback of the consortium and rare available literature, quantitative **grain losses** are rather small, ranging from 1% at port level to 7% at farm level.

Regarding qualitative losses, in order to estimate a default percentage of retained functional quality, which as stated is multi-causel, involving a.o. compositional shifts, digestibility loss and/or contamination load, a simplification was made. Metabolisable energy (ME) of the grain was chosen as a proxy, as it can shift over the storage period and integrates digestibility loss (from whatever cause), but it is specifically an animal nutrition metric. An average ME of 12 MJ / kgDM is assumed, compared to 15 MJ / kgDM for sound food grain, resulting in a 20% decline, or a 80% retained quality, which is used as a proxy default setting. As the quality damage and potential fraction of downgraded grain can vary once infested, the retained quality factor should be treated as a continuous factor, rather than a categorical threshold, and serves as an methodological choice to indicate the remaining functionality. Moreover, the quantity and quality adjustment is independent of the chosen treatment. The effect is discussed separately in the scenario assessment (section 2.4.5).

Table 2: extension of table 1 - more detailed inventoried data on grain treatment

Treatment LCI per tonne grain	Dosage	*Production*	Emissions to air	Probability of failure
No treatment (NoT)	-	-	-	95% (90 - 100%)
Fumigation (FUM)	32g	18.1 g aluminium phosphide 6.8 g ammonium carbamate 7.45 inert material	70% PH_3 (55 – 85%)	15% (10 - 20%)
K-Obiol ULV6 (KO6)	84ml	0.5 g deltamethrin 4.5 g PBO 68.9 g FAME	0.0005 % deltamethrin 0.0001 – 0.001%)	12.5% (5 – 20%)
Pirigrain 50 (PG50)	60 mL	3 g pirimiphos-methyl 48.6 g inert material	0.5% pirimiphos-methyl (0.1 – 1%)	15% (5 – 25%)
Methograin IGR ULV 30 (MG30)	40 mL	1.2 g s-methoprene *34 g FAME*	0.005% s-methoprene (0.001 – 0.01%)	25% (5-75%)
Dual application (Dual)	42+40 mL	0.25 g deltamethrin 2.26 g PBO 1.2 g s-methoprene *68 g FAME*	0.0005 % deltamethrin 0.005% s-methoprene	6.5% (3 – 10%)

To summarise, in the default assessment, for each treatment strategy, the storage of, f.i. 1000 tonne of grain requires the harvest in Europe by approximation from 173 ha, including 42 tN, 300 kgAI, 18280 Ldiesel, 16310m³ irrigation water and 2933 kWh of electricity. Grain is transported for 350 km by truck, train and barge. It requires on average a silo of 202 kg steel and 3m³ concrete, sat on a surface area of 450m² per year, taking into account a turnover of 1.2 for long term storage. The energy requirement amounts to 2190 kWh to (un)load and ventilate the grain in a clean disinfected silo with 500 gAI (from K-Obiol EC25).

To treat the grain for 12months conservation, the respective amounts of 18 kg (FUM), 0.5 kg (KO6), 3 kg (PG50), 1.2 kg (MG30) or 1.7 kg (Dual) kg active ingredient are manufactured, packaged and distributed over 825 km, and finally applied by electricity driven spraying equipment, if applicable at ULV and/or in dual application or through tablets for fumigation. Per default, 95% (NoT), 15% (FUM), 12.5% (KO6), 15% (PG50), 25% (MG30) and 6.5% (Dual) grain is lost for food, of which 3% is physically lost and 20% is lost qualitatively, overall resulting in 878 t (Not), 966 t (FUM), 972 t (KO6), 966 t (PG50), 944 t (MG30) and 985 t (Dual) respectively retained grain after 12 months of conservation, due to the considered allocation approach.

2.3 Life Cycle Impact Assessment – results

The environmental impact of grain storage treatment strategies was quantified and visualised to assess to which environmental themes and to what extent the different stages in the supply chain and related processes contribute, and more specifically the grain treatment as such. Through classification and characterisation, related direct/indirect emissions and resource use are translated into environmental ICs, and further in a single score through normalisation and weighing of the ICs. Details can be found in **Annexes 1 to 4**.

2.3.1 Single score supply chain and grain treatment

The single score (in mPts) aggregates all 16 impact categories into one weighted indicator, as a measure for the overall sustainability within the defined goal and scope and enables the identification of the environmental hotspots across the full impact profile, i.c. for each treatment per tonne of grain effectively stored. As seen in Figure 2, overall, each treatment benefits the grain storage in a sustainable way compared to no treatment (NoT), with a reduction between 16,6 and 20%, which corresponds respectively to the Methograin IGR ULV30 (MG30, s-methoprene) treatment and the dual application of the MG30 and adulticide K-Obiol ULV6 (KO6, deltamethrin). The liquid insecticide treatments with KO6 and Pirigrain 50 (PG50, pirimiphos-methyl) as well as the fumigation (FUM, phosphine) fall within the range at a 18.5 -19% reduction. Overall, given the system boundaries and data inventory as described and listed in previous sections, more than 30% of the single score for each scenario, is caused by the freshwater ecotoxicity (eTox), followed by the ICs in order of magnitude: climate change (CC; 11%), land use (LU; 11%), Particulate matter (PM; 8%), marine eutrophication (EUm; 6%), acidification (AP; 5%) and both freshwater and terrestrial eutrophication (EUfw, EUt; both 5%). Together these ICs sum up to over 80% of the single score, according to the EF method, representing the structural environmental hotspots and most relevant to the grain supply chain, with or without treatment, and these will be discussed when evaluating the impact in terms of midpoint ICs.

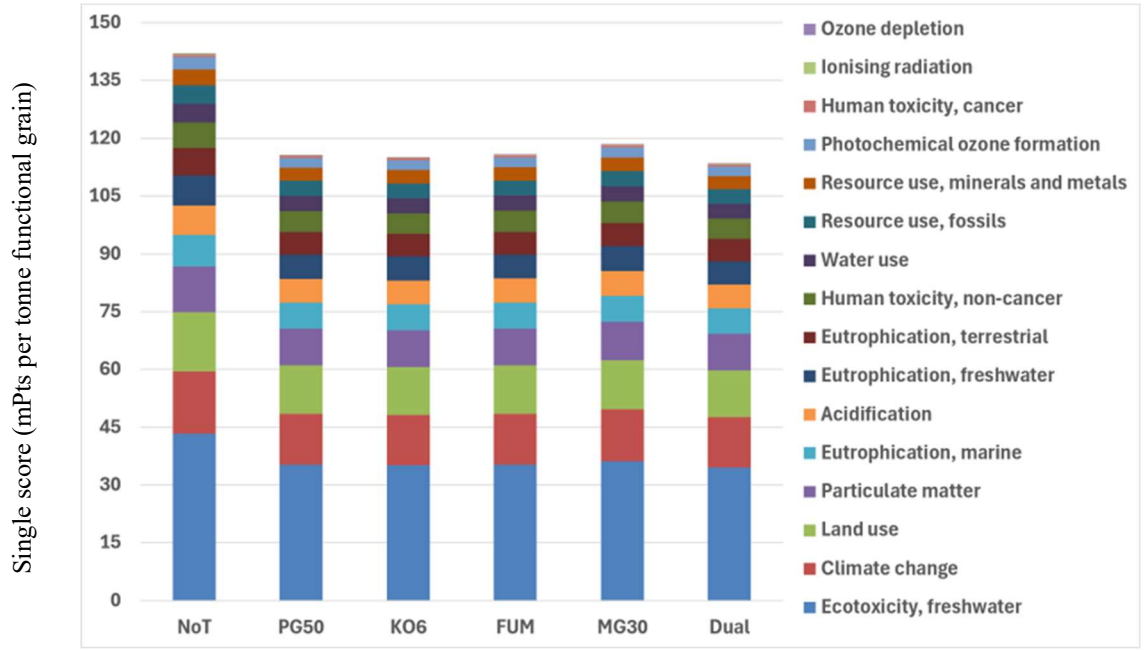


*Figure 2 Single score (mPts per tonne of functional grain) differentiated by impact categories of the different treatment scenario's: no treatment (**NoT**), Pirigrain 50 (**PG50**), K-Obiol ULV6 (**KO6**), fumigation (**FUM**), Methograin IGR ULV30 (**MG30**) and dual application of MG30 & KO6 (**Dual**).*

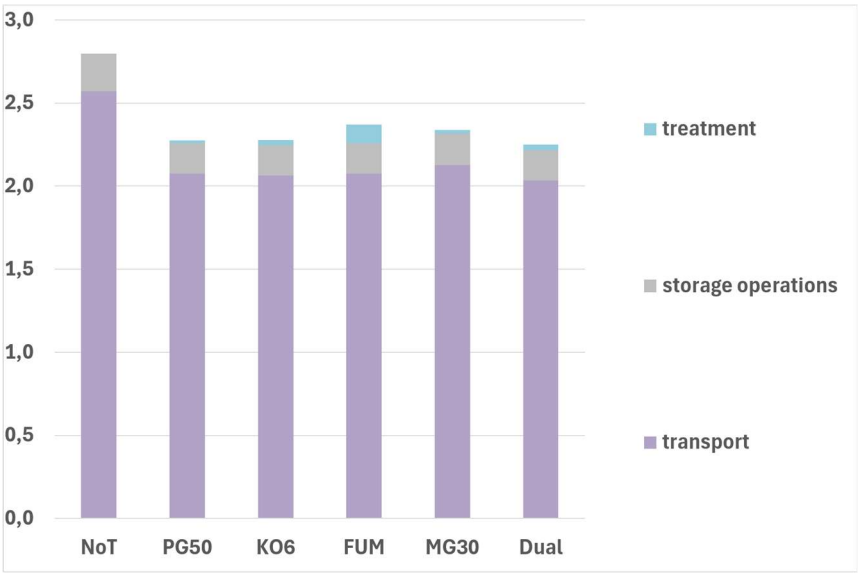
The single score can also be differentiated by the different stages of the supply chain, as shown in Figure 3. It is shown clearly the cultivation stage of the grain dominates the overall sustainability by 98%, followed by grain transport (1.8%) and minor contributions of the storage operations (0.16%) and actual treatment (0.005 - 0.1%). Regarding the storage operations (excl. treatment), the main impact comes from the operations themselves (84%), followed by the infrastructure (16%), with minor contribution from the disinfecting (0.4%).

Single score (mPts) per tonne functional grain

(1) full supply chain



(2) excl. cultivation



(3) only storage: operations and treatment

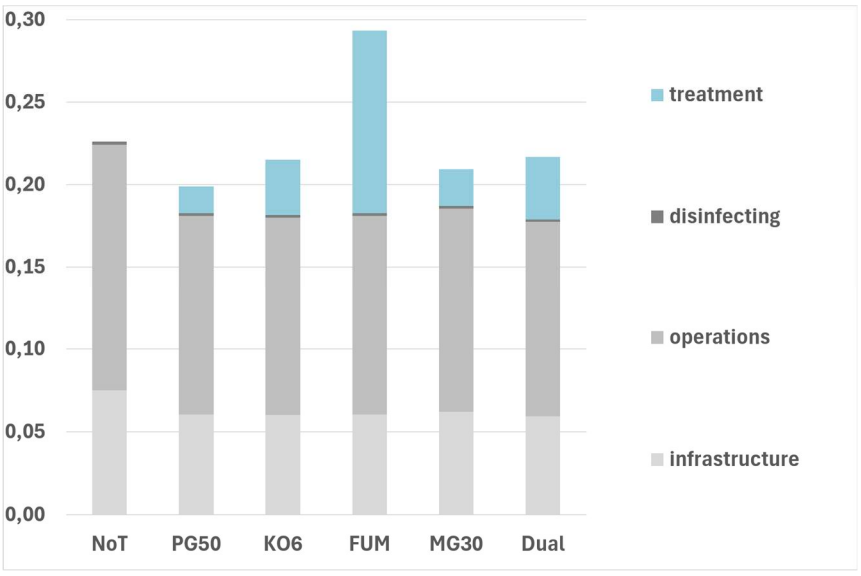


***Figure* 3** *Single score (mPts per tonne of functional grain) differentiated by the supply chain stages (UPPER), without cultivation stage (MIDDLE), and only regarding storage (LOWER) for the different treatment scenario's: no treatment (**NoT**), Pirigrain 50 (**PG50**), K-Obiol ULV6 (**KO6**), fumigation (**FUM**), Methograin IGR ULV30 (**MG30**) and dual application of MG30 & KO6 (**Dual**).*

When zoomed in to the grain treatment step per tonne effectively stored quality grain, fumigation has the highest impact, while the smallest contribution comes from the PG50 treatment, yet they all showed similar overall impact over the whole supply chain.

The relevance of the impact categories do change compared to the supply chain depending on the strategy. Regarding fumigation, the most impact is related to human toxicity, non -cancerous (HTnc; 60%), while the other treatments it is more spread: PG50 treatment entails most impact from fossil resource depletion (RDf; 32%) , CC (18%) and eTox (9%), while from the KO6, MG30 and their dual application, most impact comes from CC (17-21%); RDf (9-18%), AP (10–13%) and EUm (10-12%).

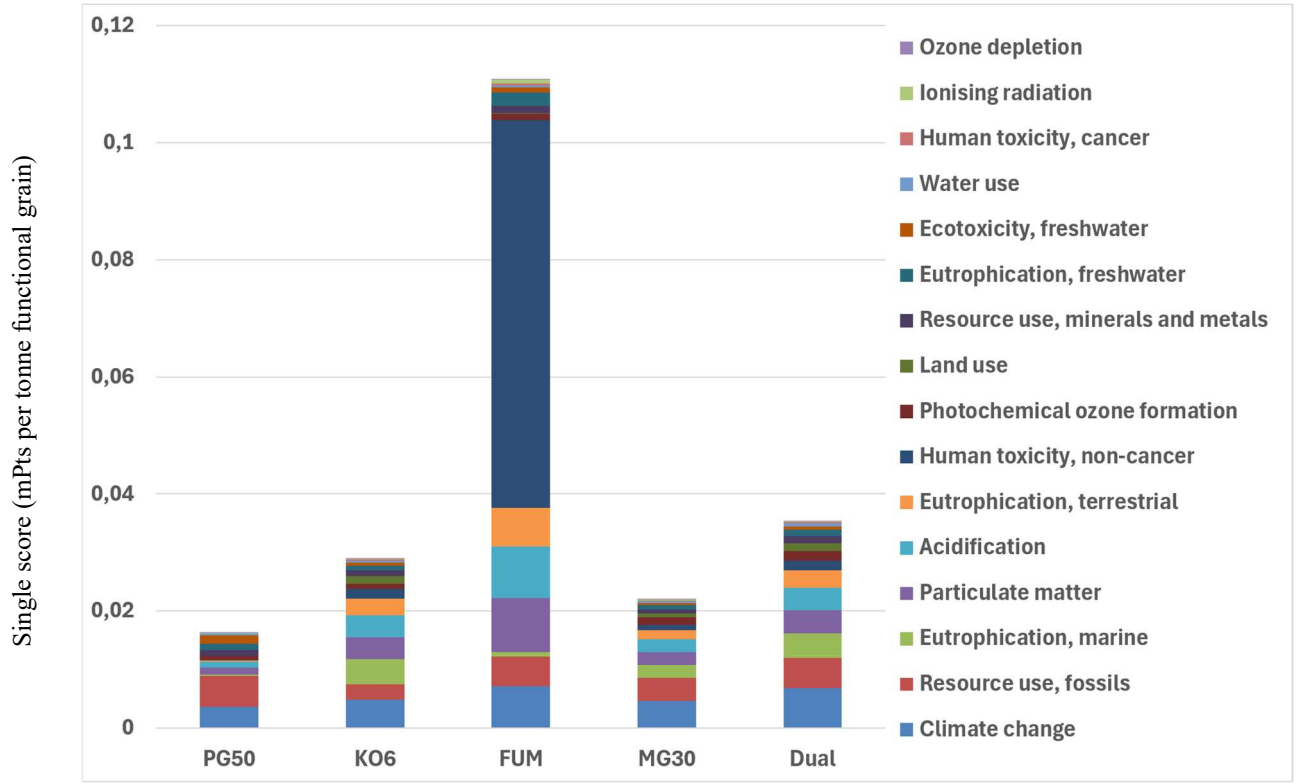


*Figure 4 Single score (mPts per tonne of functional grain) regarding the grain treatment stage, differentiated by impact categories of the different treatment scenario's: no treatment (**NoT**), Pirigrain 50 (**PG50**), K-Obiol ULV6 (**KO6**), fumigation (**FUM**), Methograin IGR ULV30 (**MG30**) and dual application of MG30 & KO6 (**Dual**).*

Again, the impact, i.c. from the grain treatment step alone, can be split in function of the related processes, as shown in Figure 5, expressed per kg active ingredient (AI) applied (left) and per tonne functional grain (right). For most treatments the manufacturing and formulation of the product has the biggest contribution (82-94%), except for fumigation (21%), followed by packaging (5-9%) and distribution (1.3-2.4%). The largest impact of fumigation is related to the emission of the phosphine gas (78.5%), while for the others, the emissions and impact of active ingredient is limited to 6% regarding PG50, 0.05-0.09% regarding KO6 and Dual, and negligible for MG30.

Per kgAI applied, most impact is caused by the deltamethrin based product, but translated per tonne of effectively stored quality grain, the difference with pirimiphos-methyl based PG50 becomes 6 times smaller, while fumigation becomes the highest impact contributor regarding the grain treatment step, taking into account the required application rates to store for 12 months and the assumed probabilities of failure.

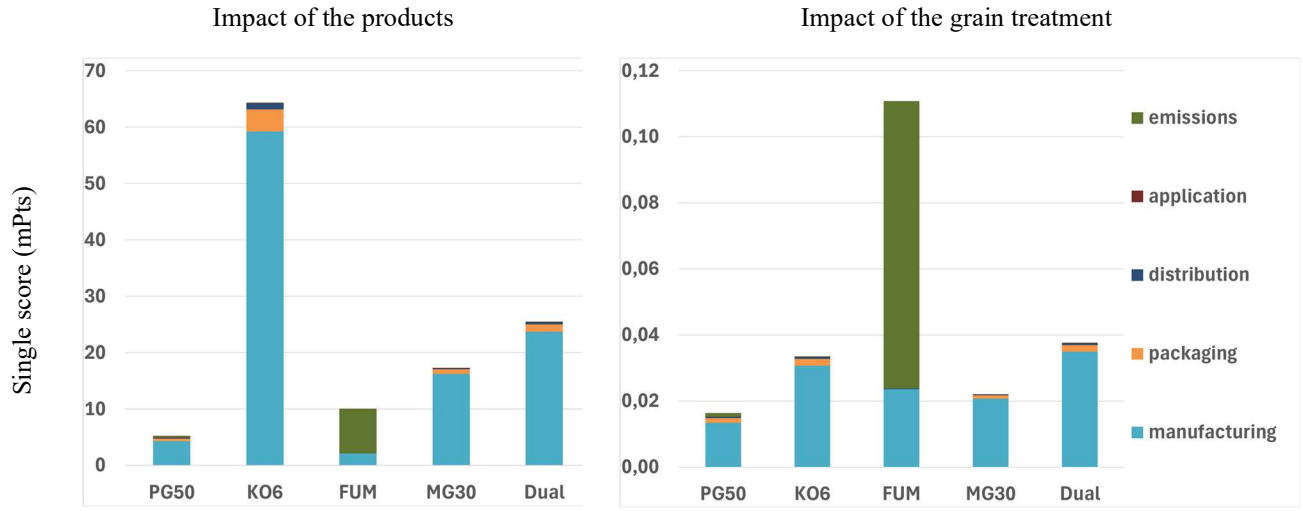


*Figure 5 Single score (mPts) regarding the treatment products (LEFT; per kg active ingredient applied) and the grain treatment stage (RIGHT; per tonne functional grain) , differentiated by the processes of the different treatment scenario's: no treatment (**NoT**), Pirigrain 50 (**PG50**), K-Obiol ULV6 (**KO6**), fumigation (**FUM**), Methograin IGR ULV30 (**MG30**) and dual application of MG30 & KO6 (**Dual**).*

2.3.2 *Hotspot analysis (midpoint IC) supply chain and grain treatment*

A first assessment is shown in Figure 6 presenting the relative contribution of the **supply chain** stages for the selected relevant environmental ICs. This highlights again the dominant impact of grain cultivation in the supply chain for all impact categories, with at least 95% due fertiliser applications, induce N_2O and NH_3 volatilisation and NO_3 leaching, causing climate change (CC), acidification (AP) and eutrophication (EU). The share in land use (LU) and freshwater ecotoxicity (eTox) is even close to 100% due to respectively the land use occupation and toxic potency of active ingredients applied by plant protection products on the crop, which are by default 100% emitted to air (9%), soil (90%) and water (1%) bodies. A small contribution, given the considered distances, is related to the grain transport, in CC leading up to 5%.

The impact from the default operations at the storage facility is limited, to max 0.4% for climate change related to the background impact regarding infrastructure and electricity generation. The grain treatment furthermore contributes even less, with a contribution limited to 0.14% depending on the strategy and IC. Overall, the extra burdens in order to store the grain after harvest are small compared to the cultivation.

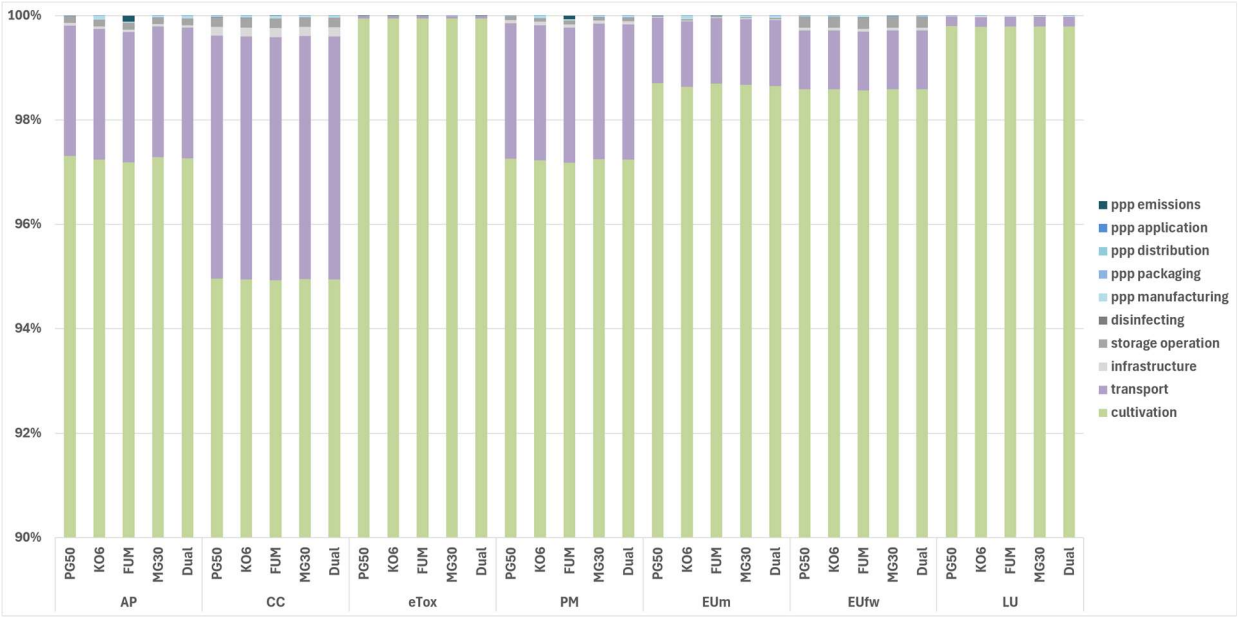


*Figure 6 Relative contribution of the grain supply chain stages to the selected impact categories: acidification (**AP**), climate change (**CC**), freshwater ecotoxicity (**eTox**), particulate matter (**PM**), marine and freshwater eutrophication (**EUm, EUfw**) and land use (**LU**).*

Focussing on the impact from **grain treatment** as such per tonne effectively stored quality grain, a few differences come up between the protection strategies regarding relevant impact categories, as shown in Figure ***7***. Not a single treatment strategy scores the worst nor the best on all considered impact categories, yet fumigation does not score well, cfr. the single score, compared to the other treatments, except for marine eutrophication and freshwater ecotoxicity to a certain extent, while the dual application of the IGR and adulticide KO6 does not perform the best in any of the categories.

Depending on the type of product and its composition, the contribution of the production (i.e. manufacturing of the active ingredient (AI), co-formulants (i.c. synergists, additives, emulsifiers,…) and solvent/carriers), to each impact category differs, as well as the potential emissions. As the single score already indicated, most burden is caused by the **production of the plant protection product** (80 – 99%), and more specifically the manufacturing and formulation of the active ingredient, additives and solvent/carriers, excluding the packaging and distribution. Except for fumigation and PG50 regarding eTox, this is valid regarding all impact categories. While the impact of production of AI (e.g. aluminium phosphide for fumigation) and co-formulants (e.g. piperonyl butoxide (PBO) in KO6 (and dual)) is mainly related to background industrial (energetic) processes, causes the production of i.c. FAME as carrier for ULV applications extra burdens to CC, EUm, AP, etc… due to agricultural production of the crop feedstock (e.g. rape seed (oil)) similar as the grain cultivation itself).

The assessment shows a small contribution of **packaging** of the, especially liquid pesticides, regarding RUf and CC (6-16%), while the transport by truck for **distribution** of the product is limited to 1% on average, up to 5%.

The **application** of the products, through electricity driven spray installations, has an even smaller contribution to the environmental impact, with less than 0.3% on average, except for the dual application strategy which is slightly higher, up to 1.7% to EUfw.

After application during storage, and when the facility is vented after fumigation, as described in previous sections, the **active ingredients can be released** to the environment, causing potential damage to the aquatic ecosystem and/or human health through inhalation or ingestion. I.c. especially fumigation shows a two-fold burden, on the one hand due to the released toxic phosphine gas contributing to eTox (up to 71%) and HTnc (up to 99.4%), and on the other hand the extra burden of reaction products, mainly NH_3 to AP, EUm and PM. Compared to the (very) low volatilisation rate of especially deltamethrin and s-methoprene, PG50s' pirimiphos-methyl does contribute to eTox up to 73%.



Figure **7** *Environmental impact of the grain treatment stage per strategy for the selected impact categories (ICs), expressed per tonne functional grain, for the different treatment scenario's: Pirigrain 50 (**PG50**), K-Obiol ULV6 (**KO6**), fumigation (**FUM**), Methograin IGR ULV30 (**MG30**) and dual application of MG30 & KO6 (**Dual**)*

2.4 Life cycle evaluation – discussion

The environmental impact of different grain storage strategies and more specifically the grain treatment within the supply chain are discussed further based on the results, addressing environmental hotspots or points of attention and potential measures, related to the considered practices and assumptions.

The overall impact of the grain supply chain up to the storage gate is dominated by grain cultivation, followed by a very small share from grain transport to the storage facility. Ultimately, the impact caused by default storage operations and the considered grain treatments is very limited. Given the intensity of the cultivation (including a.o. 100-700x more pesticide application per tonne compared to the storage application) and the similar practices within the supply chain, except for the treatment itself, the outcome depends on the probability of failure set for each treatment strategy, i.e. every ton of grain saved benefits the environmental sustainability.

Based on the baseline set of parameters, the grain storage benefits environmentally from grain treatment, preserving as much quality grain as possible, with a small tendency towards the dual application of IGR and adulticide, but the overall impact between the strategies is limited.

Regarding the impact categories, the most relevant ones are related to the grain cultivation, i.e. freshwater ecotoxicity due to pesticide application, climate change due to fertiliser induced N2O emissions and diesel use, land use, and acidification and eutrophication due to fertiliser induced N- and P-emissions to the environment. Focussing on the gain treatment (manufacturing and application), also fossil fuel depletion and human toxicity become relevant in the evaluation. No strategy scores worst or best in every impact category, and each treatment has its (dis)advantages environmentally, although fumigation shows high impact in many categories due to the active ingredient production and in addition its potential emission of phosphine, along with reaction products of ammonium carbamate. For the other pesticide treatments, the main impact is caused by industrial (energetic) processing for the production of the AI and co-formulant(s) (e.g. PBO in KO6) and/or the use of carrier, in particular FAME for ULV application has inherent burdens from the crop feedstock production.

Given the characterisation of the full production scheme, the data as collected and theoretically modelled, the assumptions made, and the database proxies used, the results inherently contain a degree of uncertainty and/or inaccuracy, but the main findings provide insight into the environmental sustainability of the different treatment strategies and reveal the areas of focus. Corresponding to the different stages of the grain supply chain and the identified hotspots, the next section will address the most relevant parameters subject to lack of (accurate) data, variability and the assumptions made.

2.4.1 Grain cultivation

Whether a specific type of grain (i.c. wheat, barley or maize) would be considered in the assessment, or the region of cultivation, it doesn't change the outcome of the study comparing the protection strategies and identifying the hotspots. As shown in Figure 8, i.c. for the dual application scenario, the absolute impact does change, depending on the trade-off between inputs and yield, yet, the share of cultivation to the overall impact is barely affected (+/-1%), although the effect is mixed across the different impact categories.

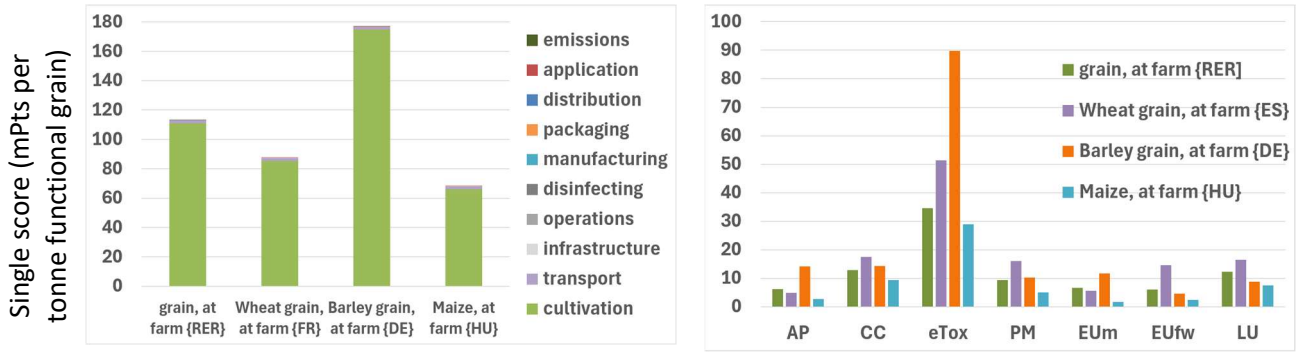


*Figure 8 single score (mPts per tonne functional grain)) of grain supply chain (i.c. dual application treatment) regarding different grain cultivations, differentiated per supply chain proces (LEFT) and per impact category (RIGHT): acidification (**AP**), climate change (**CC**), freshwater ecotoxicity (**eTox**), particulate matter (**PM**), marine and freshwater eutrophication (**EUm, EUfw**), land use (**LU**).*

*2.4.2 **Grain transport***

Although grain transport routes and corresponding modi are unlikely to be managed flexible, it goes without saying, any avoided km of transport is beneficial. If train or barge can replace the truck for (long-distance) distribution, the overall impact of transport could be reduced by 50% approximated for that share, reflecting higher efficiencies driven by higher loads and lower fuel consumption per tonne of cargo and avoided tire abrasion and network infrastructure. Nevertheless, from the sLCA (Moshkin *et al*. (2025) D4.8) large routes, from a Hungarian farm over an Italian trader to the German port, would mean a fourfold of the distances assumed in the LCA, what would result in a 5% increase of the overall impact.

*2.4.3 **Grain storage operations***

Given the limited contribution of the default storage operations to the overall impact, including infrastructure, equipment and energy use, a scenario considering 100% green energy would reduce the overall impact by 0.1%, still it entails avoided resource depletion.

*2.4.4 **Grain treatment***

Also the treatment, involving both the production and application of the plant protection products, has relatively a negligible contribution to the overall sustainability of the supply chain of stored grain. Comparing the different strategies, the assessment shows a small benefit of 1% from the dual application over the fumigation and liquid insecticides, and 3.5% in particular over the MG30. Along with the different impacts per kgAI, mainly favouring PG50, FUM and to certain extent MG30, it emphasises the effect of relative dosage in each strategy in combination with the expected probability of failure (addressed further in section 2.4.5) to retain qualitative grain stored over 12 months. The different impact profile of the treatment strategies is traced back to the specific composition of the products. Overall, the impact relates to the manufacturing but mainly formulation of the products in most categories, and to the emissions regarding fumigation.

The impact of AI **manufacturing** is rather limited, except for fumigation due to high dosage and for MG30 due to high energetic processing. Bare in mind, this comprises on the one hand background modelling of common active ingredients (i.c. deltamethrin, pirimiphos-methyl and phosphine) reflecting efficient high volume mature compound manufacturing, and on the other hand primary data of partner Babolna on s-methoprene production which still shows a product under development with room for improvements. Besides the AI, the assessment shows co-formulants (i.c. synergists, emulsifiers, etc..) added into the product for optimal performance, causes more burden, especially regarding KO6s' piperonyl butoxide (PBO) on eTox. If an energy reduction of the manufacturing process by 50% would be obtained to close the gap, along with a switch to 100% renewable energy sources, it would mean a reduction by respectively 6% and 4% of CC and 5% and 3% of RUf, and overall for the manufacturing a reduction in single score by 1.6% and 1% through the respective measures. Regarding the ULV applied products, there is extra impact due to the FAME used as carrier causing agricultural burdens in the background (cfr. fertiliser and pesticide induced field emissions, land use,…), as it is a.o. sourced from crop feedstocks, with rapeseed oil being the dominant one. Its impact exceeds the one of petroleum-derived hydrocarbons used as solvents, i.c. for PG50. FAME, alternative sourced from f.i. used cooking oil (UCO) as suggested by Purkait *et al.* (2020, 2024), could overcome this burden. Subject to verification and regulation, merely as an indication, a switch to 100% UCO, as shown in Figure 9 (left), would reduce the manufacturing and formulation impact of the ULV strategies by 72%, 54% and 62% for respectively KO6, MG30 and Dual which would favour them over the other strategies per tonne functional grain.

At the current development stage, the default **application rate** of MG30 is set at 40mL per tonne of grain. However, to assess the potential impact of the IGR, half the dose is considered which might still prove sufficient level of efficacy. As shown in Figure 9 (right),this would reduce the impact of the MG30 and Dual strategy regarding the grain treatment by 50% and 28% respectively, even by 4.8% considering the supply chain.

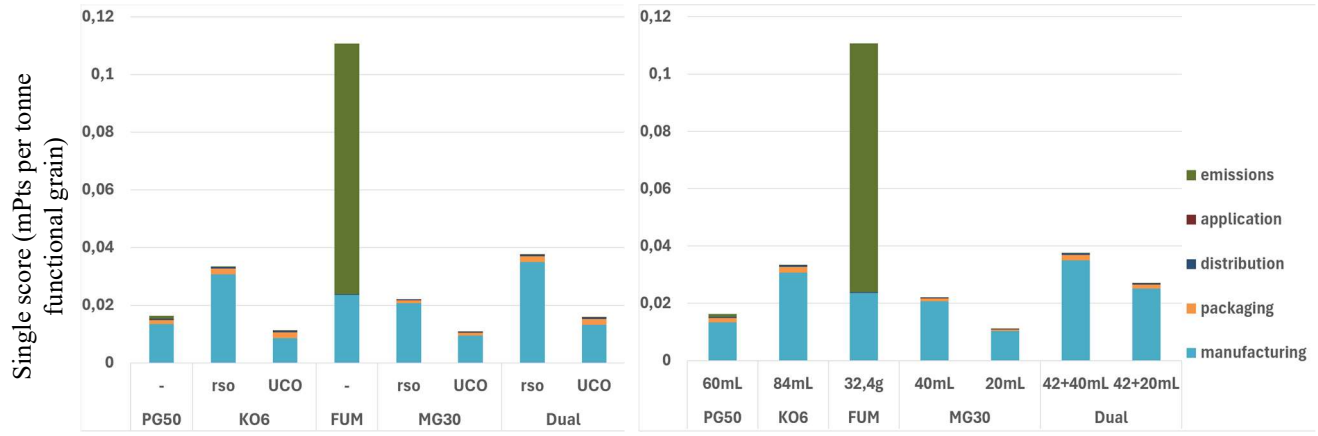


*Figure 9 Scenario assessment regarding the replacement of rapeseed oil (rso) by used cooking oil (UCO) as source for the FAME carrier (left) and the reduction of s-methoprene by 50% in MG30 and Dual (right); both showing the relative contribution of the environmental impact to the single score of the grain treatment stage per tonne of functional grain with the different treatment scenario's: no treatment (NoT), Pirigrain 50 (**PG50**), K-Obiol ULV6 (**KO6**), fumigation (**FUM**), Methograin IGR ULV30 (**MG30**) and dual application of MG30 & KO6 (**Dual**).*

Regarding the potential **emissions** after application, extra burdens from fumigation are related to the release of CO_2 and NH_3 decomposed from the additive ammonium carbamate, mainly increasing the impact regarding AP, PM and EUm. Besides the immense impact on HTnc, phosphine also contributes to the eTox, although PG50s' pirimiphos-methyl shows a much higher eTox potential almost twice per tonne of functional grain, considering a third of AI dosage. Given the low volatilisation potential of the considered active ingredients, except for phosphine, a sensitivity analysis considering even a 100% variation, and 21% for fumigation, would change the impact of the grain treatment of PG50 and FUM by 6.4% and 16.8% respectively, but doesn't offset relative differences.

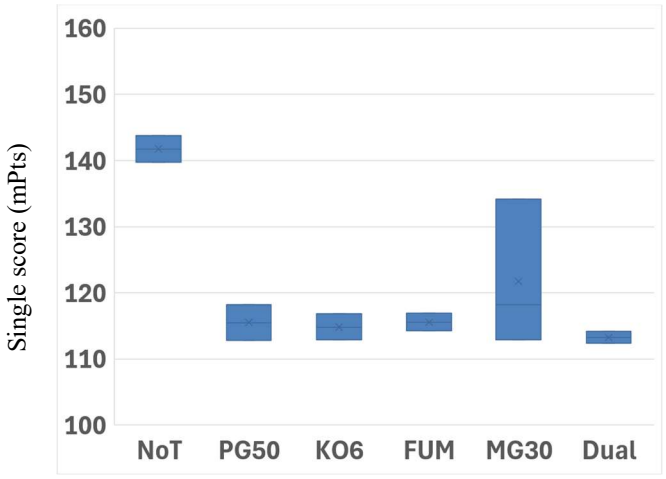
2.4.5 Grain losses

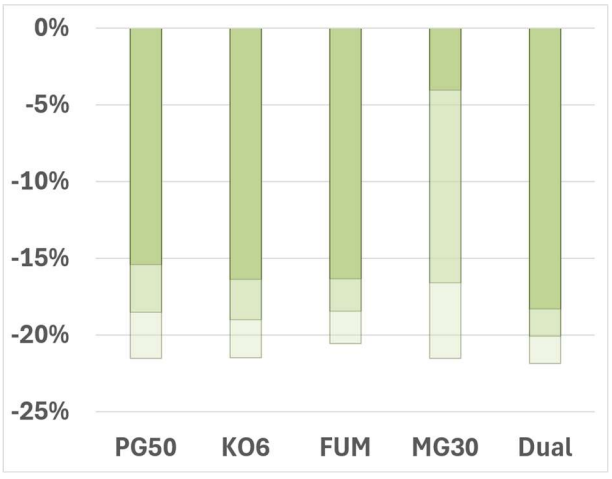
To assess the impact of changes in grain losses, the baseline input parameters set in the inventory for the default assessment, can be adjusted with discrete levels of change corresponding to potential variability of the probability of failure and the quantitative and qualitative grain losses.

As the assessment showed a limited contribution of grain treatment to the overall impact of the supply chain, the difference between the strategies highly dependent on the potential performance to protect the grain from downgrading over 12 months of storage. In order to account for their variability, the best possible estimates for the **probabilities of failure** (pb) set in the CBA report (Moshkin *et al*. (2025) D4.9) for each treatment per region per scale of trade served as a range for a scenario analysis on the environmental impact. As shown in Figure 10, given the ranges of probabilities of failure per treatment reflecting differences in a.o. weather conditions, management and population resistance, the differences between treatments is not very distinct, except for the MG30 treatment when some grain entering the storage may already be infested, hence the pf of 75%, and a limited reduction by 4% compared to the NoT scenario. The assessment further suggests the grain storage might benefit from a dual application strategy compared to the others considering the worst conditions (at least 'min' reduction at highest pf values), but that becomes negligible when all treatments perform at their best (potentially 'max' reduction at lowest pf values).

The default assessment assumes the downgraded fraction of the stored grain suffers from both quantitative as qualitative losses, taken into account through the functional unit, expressing the impact of the strategy per tonne of functional grain.

As addressed above, **quantitative losses** of the downgraded grain are considered limited, but might still vary depending on the region and/or scale of storage (i.e. at farm, trader or port), from 1 to 7%. A corresponding sensitivity analysis shows an increasing benefit of the treatments with better expected performance, i.e. lower probability of failure. For each increase of quantitative loss by 1% (without potential corresponding quality loss), the impact per tonne functional grain will increase by 1% for NoT, 0.21% for MG30, 0.1% for PG50, KO6 and FUM, and 0.05% for Dual application.





pf	NoT	PG50	KO6	FUM	MG30	Dual
max	100%	25%	20%	20%	75%	10%
def	95%	15%	12.5%	15%	25%	6.5%
min	90%	5%	5%	10%	5%	3%

	PG50	KO6	FUM	MG30	Dual
min	-15.4%	-16.4%	-16.3%	-4%	-18.3%
def	-18.5%	-19%	-18.5%	-16.6%	-20.1%
max	-21.5%	-21.5%	-20.5%	-21.5%	-21.8%

*Figure 10 Single score impact (LEFT; per tonne functional grain)) depending on the range of probabilities of failure (pf) and the corresponding potential reduction compared to NoT (RIGHT; %) per treatment scenario: no treatment (**NoT**: 90-100%), Pirigrain 50 (PG50:5-25%), K-Obiol ULV6 (**KO6**: 5-20%), fumigation (**FUM**: 10-20%), Methograin IGR ULV30 (**MG30**: 5-75%) and dual application of MG30 & KO6 (**Dual**: 3-10%), given the corresponding default probabilities of failure*

Given the uncertainty on risks of **qualitatively losses**, the remaining amount of functional grain after storage can be expected to fluctuate. While the default assessment considered a 80% remaining qualitative functional grain which implies a remaining valorisation as feed, biofuel, anaerobic digestion and/or compost, the variability of potential damage and the effect on the assessed environmental impact is shown in Figure 11. It illustrates how the severity of damage or remained qualitative functional downgraded grain affects the impact score of the treatment strategy. The lower the remaining quality of the downgraded fraction of grain, the higher the impact, and the more distinct the difference between treatments, which reflects the performance of the treatment to protect the grain. Given the default probabilities of failure, for every decrease in quality by 20%, the impact of the strategy per tonne of functional grain increases overall by 5-6% for MG30, 2-3% for PG50, KO6 and FUM, and is limited to 1% for Dual application. Regarding the NoT scenario, whereas the difference in impact with the treatment strategies amounted to 20% under the default assessment, this would be limited to 2.5% under 0% loss assumptions, but would be substantial up to 95% under 100% loss of quality of the downgraded grain (cut off in Figure 11).

The latter scenario would also reflect the implications if the (functional unit of the) assessment would only consider the remaining food grade grain (based on the probability of failure) to which all impact of the system would be attributed to.

To what extent the qualitative losses in practice will vary, is hard to pinpoint given the inherent variability depending on a.o. the environment, management and type of pest infestation degree and resistance, yet, the assessment indicates the implications of potential degree of downgrade.

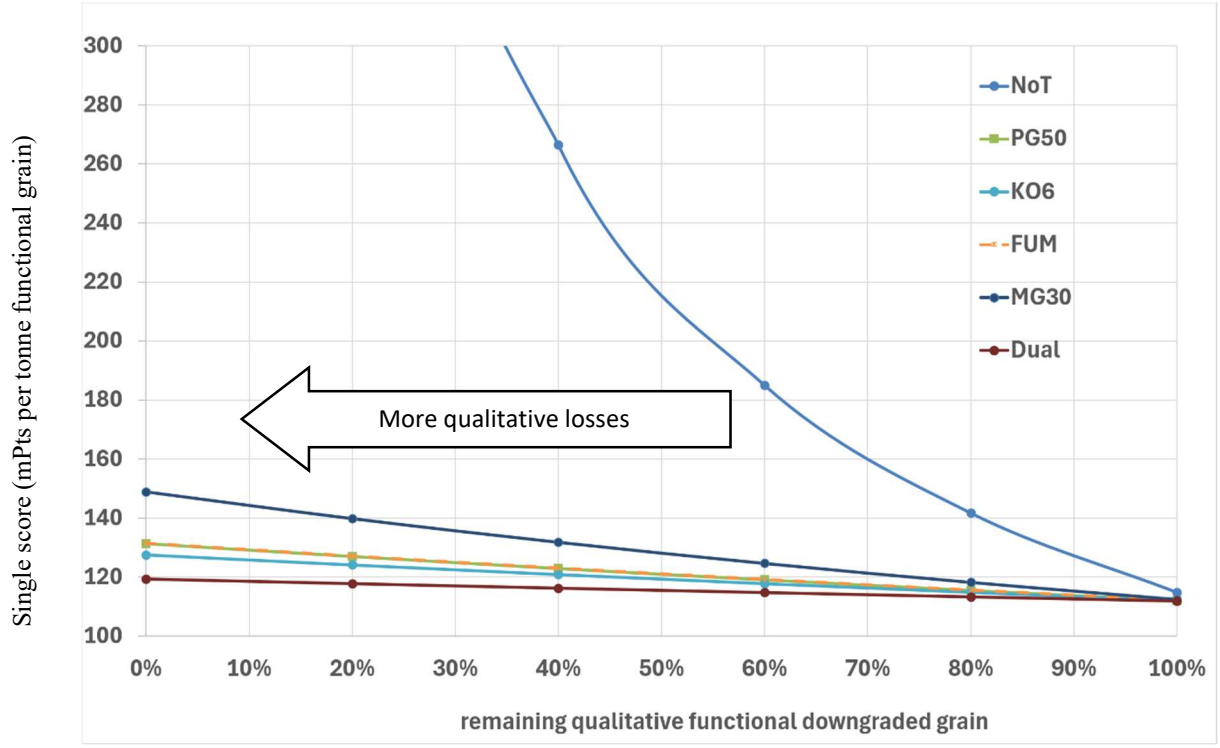


*Figure 11 Single score (mPts per tonne functional grain) depending on the remaining qualitatively functional downgraded grain for all the different treatment scenario's (**NoT**; cut off for lowest remaining quality), Pirigrain 50 (**PG50**), K-Obiol ULV6 (**KO6**), fumigation (**FUM**), Methograin IGR ULV30 (**MG30**) and dual application of MG30 & KO6 (**Dual**), given the corresponding default probabilities of failure*

2.4.6 novIGRain potential

Ultimately, a final assessment considers the "worst", "default (def)" (used for the main assessment) and "best" conditions, listed in Table 3, reflecting the outer values of ranges regarding probability of failure, quantitative and qualitative losses, and potential application emissions during/after storage for all treatments, but also specific potential measures regarding decreased dosage of the IGR, its potential energy reduction during manufacturing, and the more sustainably sourced FAME for ULV applications.

Table 3. Life cycle inventory parameters of the grain supply chain.

"worst" – "best" conditions							
	condition	NoT	PG50	KO6	FUM	MG30	Dual
Probability of failure (pf)	worst	100%	25%	20%	20%	75%	10%
	best	90%	5%	5%	10%	5%	3%
Remaining quantitative grain (%)	worst				7%		
	best				1%		
Remaining quanlitative grain (%)	worst				0%		
	best				99%		
Application rate (mL/tonne; g/t for FUM)	worst	-	60	84	10.6	40	42(KO6)+40(MG30)
	best	-	60	84	10.6	20	42(KO6)+20(MG30)
Energy efficient AI manufacturing	worst	By default					
	best					-50%	-50% for MG30
Sustainably sourced FAME	worst	-	-	rso	-	rso	rso
	best	-	-	uco	-	uco	uco

As shown in Figure 12, this assessment shows that the grain storage benefits environmentally from treatment, especially with increasing risk on grain losses overall. While in the default assessment, a reduction between 16 and 20% compared to NoT is expected, with a small preference to the dual application by 2% (4% with MG30) amongst the treatments, these differences decrease to 0.02% (0.14% with FUM) under the best conditions and their performance to preserve the most qualitative grain. On the other hand, under the highest risk of failure and the worst conditions with 100% qualitative losses of the downgraded grain (i.e. for NoT 100% of grain is qualitatively lost to valorise and thus to attribute the impact to), the impact of the dual application shows a reduced impact of 11% amongst the other strategies, again taken into account the dominant impact of grain cultivation and the difference in application rates of the active ingredients per tonne of grain stored.

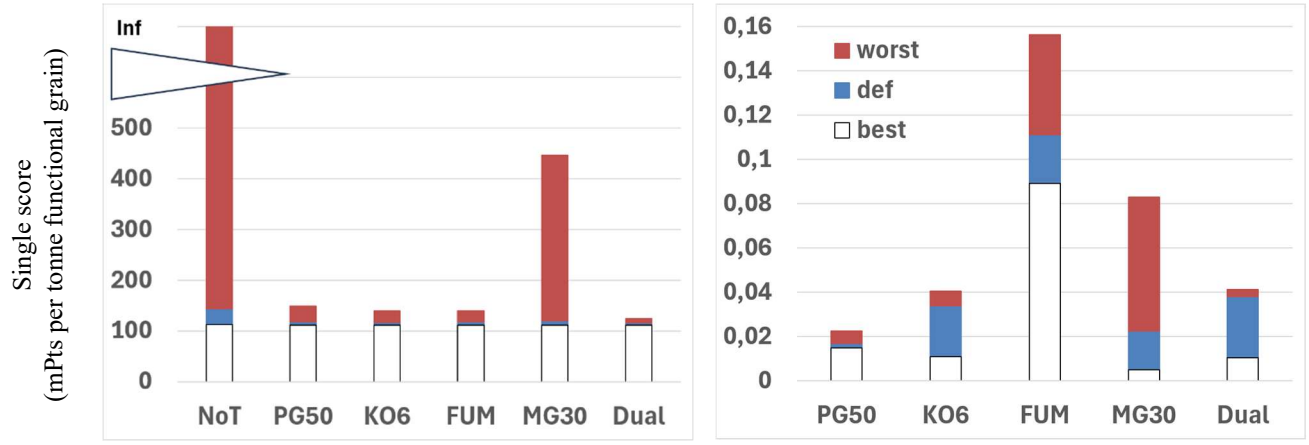


*Figure 12 Scenario assessment of the single score (mPts per tonne functional grain) of the supply chain (LEFT) and grain treatment (RIGHT) depending on the "worst", "default (def)" and "best" conditions regarding the performance and potential measures of the treatment strategies: no treatment (**NoT**), Pirigrain 50 (**PG50**), K-Obiol ULV6 (**KO6**), fumigation (**FUM**), Methograin IGR ULV30 (**MG30**) and dual application of MG30 & KO6 (**Dual**).*

2.5 Conclusion and recommendations

The LCA study provides insight into the environmental impact of grain storage over the supply chain, and the grain treatment in particular, depending on different strategies. Overall, given the goal and scope of the assessment and the hybrid inventoried data, both from primary sources, LCA database as expert judgements, the largest environmental impacts were traced back to the following key variables:

- **Cultivation** dominates the impact (±98%) of the supply chain of grain up until the grain storage gate, due to intensive practices causing typical agricultural burdens to freshwater ecotoxicity (related to pesticide application) and climate change, eutrophication, acidification, particulate matter (related to fertiliser application) and land use.
- Grain **transport** has a small impact (±1.8%)), relatively mainly to climate change, acidification and particulate matter and eutrophication, due to both fuel combustion (CO_2, NO_x, SO_2, …) as background emissions related to fuel production and the network infrastructure. It does however depend on the actual transport distances, and transport by train or barge is preferred environmentally over truck transport if feasible
- Also default **storage operations**, including (un)loading, ventilation of the grain and necessary disinfecting of the grain storing silo's, has a limited impact (±0.16%), mainly caused by the energy consumption due to the emissions related to electricity generation.
- The least impact (0.01-0.1%) is relatively caused by the actual grain **treatment**. Overall, the manufacturing and formulation of the liquid products cause the main burden, while for fumigation it is related to the human toxicity potential of the emitted phosphine. Besides the active ingredient production, also specific burdens are caused by the co-formulant products, in particular from PBO production, and by the FAME carrier for ULV application, which are related to the agricultural impact of the sourced rapeseed cultivation.
- A crucial factor determining the final environmental impact of the strategy is the expected **grain losses** overall, which depend on the one hand on the strategy performance to ensure safe food grade grain (determined by the estimated probability of failure) and on the other hand on the quantitative, but mainly qualitative losses of the downgraded grain.
- Due to the dominant impact of grain cultivation, the differences in impact between the treatment strategies are limited, especially under the most optimal conditions. However, under severe conditions, implying each their highest risks of failure and the highest losses in quantity and quality overall, the environmental assessment tends to favour the dual application over the other common strategies.

Within the scope of the environmental assessment, focussing on the foreground system of grain storage and the treatment in particular, the following **areas of focus** are highlighted:

- As the **active ingredient manufacturing** of s-methoprene for the Methograin IGR ULV 30 product is under development, there is room for improvement on the energy consumption (besides renewably sourced) and thus its environmental impact compared to the common adulticide manufacturing
- As the **ULV application** is based on a FAME carrier, commonly sourced from rapeseed oil, the environmental impact of these strategies would benefit from higher generation sourced feedstocks, f.i. based on residue oil processing, if it would meet the regulation standards.
- Ultimately, but obviously, the main goal and benefit to the environment is to prevent any kind of grain loss, in the first place regarding the food grade grain, and secondly regarding the quantity and especially quality of downgraded grain.

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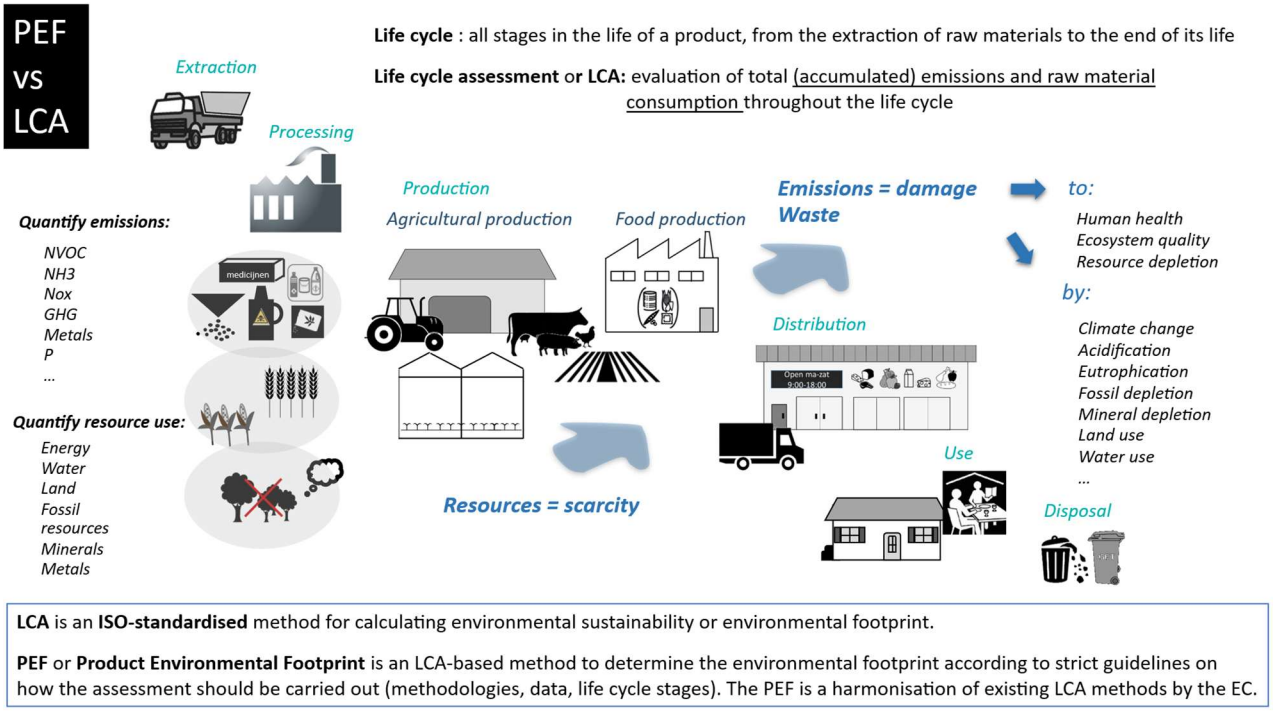
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4 ANNEXES

Annex 1: Detailed description of the LCA methodology

Life cycle assessment (LCA) is a measurement and evaluation method used to quantify the environmental sustainability of a product or service throughout its entire life cycle (from raw materials to production, use and waste disposal). LCA calculates the environmental impact in various impact categories (including climate change, eutrophication, acidification, toxicity, etc.) and the negative contribution to human health, ecosystem quality and resource scarcity. The method is ISO-standardised[1], which means that there are certain guidelines that the LCA researcher must adhere to. The figure below provides a graphical summary of the method, illustrated for food products.



The product **life cycle** is shown in the centre, with the different **life stages**: extraction of raw materials; processing of raw materials into semi-finished or finished products that are purchased for the actual production process in the foreground (for food: including planting material, crop protection products, infrastructure, etc.); actual production (for food: primary food production and food processing in the food industry); distribution (for food via supermarkets, grocery stores, short chains, etc.); use phase (for food: consumption of food at home, in a restaurant, in a canteen at work, etc.); waste phase (for food: composting of food waste, recycling or disposal of packaging, etc.).

Raw materials are used in the various life stages, and **emissions** and **waste** are released into the environment (soil, water, air). Because **raw materials** are scarce and emissions and waste can cause damage to people and the environment, they are inventoried, quantified and translated into **damage** to the environment and humans – divided according to environmental themes or impact categories. This is summarised in the **environmental profile** of the product. The damage caused in the various environmental themes will ultimately also lead to a negative impact on human health, ecosystem quality and raw material scarcity. This damage is quantified on the basis of further risk assessments and by combining contributing environmental impacts. The **PEF method** is based on LCA but imposes stricter guidelines so that PEF studies can be compared with each other. This is a **harmonisation** of the existing LCAs for product groups. **Annex 4** is providing a glossary of specific terms and concepts used in LCA.

[1] ISO (2006a) Environmental management — Life cycle assessment — Principles and framework, ISO 14040:2006(E). doi:10.1136/bmj.332.7550.1107.

ISO (2006b) Environmental management — Life cycle assessment — Requirements and guidelines, ISO 14044:2006(E).

Annex 2: Description of the 16 EF impact categories and their units

Impact category	Unit	Description
Acidification potential	mol H^+ eq. (hydrogen ions)	Indicator for the potential acidification of soils and water as a result of gaseous emissions such as nitrogen oxides and sulphur oxides
Climate change	kg CO_2 eq. (carbon dioxide)	Indicator of potential global warming due to greenhouse gas emissions
Ecotoxicity of the fresh-water environment	CTUe (comparative toxic units, ecosystem)	Impact on freshwater organisms of toxic substances that end up in the environment
Eutrophication of the freshwater environment	kg P eq. (phosphate)	Indicator of the enrichment of the freshwater ecosystem with nutrients as a result of the emission of nitrogen- and phosphorus-containing compounds
Eutrophication of the marine environment	kg N eq. (nitrogen)	Indicator for the enrichment of the marine ecosystem with nutrients as a result of the emission of nitrogen-containing compounds.
Eutrophication of the terrestrial environment	mol N eq. (nitrogen)	Indicator of the enrichment of the terrestrial ecosystem with nutrients as a result of the emission of nitrogen-containing compounds
Human toxicity, carcinogenic	CTUh (comparative toxic units, human)	Impact on humans of toxic substances that end up in the environment; a distinction is made between carcinogenic and non-carcinogenic toxic substances
Human toxicity, non-carcinogenic		
Ionising radiation	kBq U-235 eq. (kilobecquerel)	Damage to human health and ecosystems associated with the emission of radionuclides
Land use	Pt (points, soil quality index, dimensionless)	Measure of change in soil quality (biotic production, erosion resistance, mechanical filtration)
Ozone depletion	kg CFC-11 eq. (chlorofluorocarbon)	Indicator for gaseous emissions that cause the depletion of the ozone layer in the stratosphere
Particulate matter formation	Disease incidence	Indicator of potential cases of disease due to particulate matter emissions
Photochemical ozone formation	kg NMVOC eq. (non-methane volatile organic compounds)	Indicator for the emission of gases that influence the formation of ozone in the lower atmosphere (smog) due to photochemical catalytic reactions under the influence of sunlight
Fossil energy resource depletion	MJ (net cal. Value)	Indicator of the depletion of natural fossil raw materials
Mineral resource depletion (minerals, metals)	kg Sb eq. (antimony)	Indicator for the depletion of natural non-fossil raw materials
Depletion of water resources	m^3 water eq. of deprived water (water extraction corrected for water scarcity)	Indicator of the relative amount of water used, based on regional scarcity indicators for water

Annex 3: Normalisation and weighting factors for calculating the EF single score

Table below shows the normalisation (impact per person, reference year 2010, population 6 895 889 018 persons) and weighting factor per impact category for calculating the single score impact according to the EF 3.1 method.[2]

Impact category	Abbreviation	Normalisation factor unit	Normalisation factor	Weighting factor (%)
Acidification potential	AP	mol H^+ eq./person	5.56E+01	6.20
Climate change	CC	kg CO_2 eq./person	7.55E+03	21.06
Ecotoxicity of the freshwater environment	eTox	CTUe/person	5.67E+04	1.92
Eutrophication of the freshwater environment	EUfw	kg P eq./person	1.61E+00	2.80
Eutrophication of the marine environment	EUm	kg N eq./person	1.95E+01	2.96
Eutrophication of the terrestrial environment	EUt	mol N eq./person	1.77E+02	3.71
Human toxicity, carcinogenic	HTox,c	CTUh/person	1.73E-05	2.13
Human toxicity, non-carcinogenic	HTox,nc	CTUh/person	1.29E-04	1.84
Ionising radiation	IR	kBq U-235 eq./person	4.22E+03	5.01
Land use	LU	pt/person	8.19E+05	7.94
Ozone depletion	OD	kg CFC-11 eq./person	5.23E-02	6.31
Particulate matter formation	PM	disease incidences/person	5.95E-04	8.96
Photochemical ozone formation	POF	kg NMVOC eq./person	4.09E+01	4.78
Fossil energy resource depletion	RUf	MJ/person	6.50E+04	8.32
Mineral resource depletion (minerals, metals)	RUm	kg Sb eq./person	6.36E-02	7.55
Depletion of water resources	WU	m^3 water eq of deprived water/person	1.15E+04	8.51

[2] Normalisation_Weighting_Factors_EF_3.1.xlsx (live.com)

Annex 4: Glossary related to life cycle assessment

Allocation. The application of a distribution or allocation key to assign or distribute the total (environmental) impact of a production process to different end products, both main and by-products. This allocation can be applied to both, input flows (= output from another multifunctional system) and output flows from the system under consideration. Allocation can be done in various ways. Broadly speaking, the following three allocation keys are commonly used: based on the economic value of the output flows (economic allocation), based on a physical characteristic, e.g. the mass of the output flows (physical allocation), or based on the energy value of the output flows (energy allocation). Economic allocation is the most commonly used method, but, depending on the guidelines and type of process/product, preference may be given to, for example, biophysical allocation (e.g. in the production of milk and meat) or energy allocation (commonly used for energy carriers).

AR: **Assessment report**. Report by the International Panel on Climate Change (IPCC) containing all the latest data on climate change. Facts, technical descriptions and mitigation and adaptation measures are included in the various sections of the AR.

AoP: Areas of protection. Three areas that must be protected from an environmental perspective and against which potential environmental sustainability is weighed: human health, ecosystem quality, and resource scarcity. The AoPs are located at the end point of the impact pathway or cause-and-effect chain. They are also referred to as endpoint categories. The table below summarises this.

The three areas that need to be protected from an environmental perspective and that are considered by life cycle assessment are shown here below with their indicators and characterisation factors.

Domain	Indicator	Characterisation factor	Unit
Human health	Damage to human health	DALY = disability-adjusted loss of life years	Year
Ecosystem quality	Damage to ecosystem quality	Time-integrated species loss	Species*year
Resource scarcity	Damage to resources availability	Surplus cost*	Dollar ($)

*Surplus cost in dollar are the additional costs required to extract mineral and fossil raw materials in the future; these increase as the raw material becomes scarcer.

Background data. Data relating to the purchased products or inputs, both materials and energy and their production, including the quantity and nature of the related waste streams and emissions.

CFP: Carbon footprint. The carbon footprint expresses the extent to which a production process contributes to global warming. This is reported as the sum of the total warming effect or the "global warming potential" of all greenhouse gases emitted during the production process.

Characterisation. Part of the impact assessment. During this step, emissions and raw materials are converted into impact scores using characterisation factors. This can be done in two ways: halfway through the impact pathway – referred to as midpoint characterisation – and at the end of the impact pathway – referred to as endpoint characterisation. The environmental impact of the inputs and outputs of the system ("elementary flows") is quantified in this way, converted into a common unit if necessary, and aggregated per impact category considered. Conversion to a common unit is necessary for those impact categories to which different emissions contribute, such as the IC "climate change" to which the various greenhouse gases contribute. The effect of these emissions must be added up in order to ultimately summarise them in a single indicator, expressed in equivalents (e.g. CO_2-equivalent emissions). The result of the midpoint characterisation is the indicator results for the impact categories. The results obtained per impact category can then be further translated into damage to the Areas of Protection or protected areas on the basis of characterisation factors linked to the endpoint categories. This conversion is based on risk models. The

further down the impact pathway or cause-effect chain the evaluation takes place, the greater the uncertainty involved.

Characterisation factor. Characterisation factors reflect the environmental impact per unit of stressor, e.g. per kg of raw material used or per kg of emissions caused. Characterisation factors are derived halfway through and at the end of the impact pathway, which is called midpoint and endpoint characterisation.

Classification. Part of the impact assessment. Grouping of the various raw materials and emissions from the LCI or inventory and classification according to their potential to contribute to respective environmental impact categories. During classification, it is determined to which environmental problems the study object contributes as a result of the directly and indirectly used raw materials and emissions caused. For example, all greenhouse gases are grouped and assigned to the climate change impact category because they contribute to climate change. All acidifying emissions, such as nitrogen oxides (NOx) and ammonia, are grouped and assigned to the impact category "acidification". Classification is followed by characterisation.

CO_2-eq: CO_2-equivalents. CO_2-equivalents quantify how strong the warming effect of a greenhouse gas is. Not all greenhouse gases have the same warming effect. CO_2-equivalents are used to compare the impact these gases have on the environment and to express the amount of greenhouse gases in the atmosphere quantitatively and in a single figure. The CO_2-equivalent of a particular greenhouse gas is the amount of CO_2 (in kg) needed to cause the same warming within a given time horizon. The conversion into CO_2-equivalents therefore depends on the time horizon being considered: e.g. 20 years or 100 years. This is because the effect of a greenhouse gas varies over time. On the one hand, a greenhouse gas has a specific residence time in the atmosphere, and on the other hand, the interaction of the gas with the atmosphere follows a certain pattern over time. Methane has a greater impact when viewed over a period of 20 years than over a period of 100 years because it is a gas that breaks down relatively quickly in the atmosphere. For nitrous oxide, the values for 20 and 100 years are close together.

When calculating a carbon footprint, the time horizon and source used for the global warming potential or GWP values must always be documented. The table belopw shows these values for methane and nitrous oxide. CO_2 is the reference gas.

GWP values or CO_2-equivalents based on the 6th Assessment Report of the IPCC[3] are shown below.

Greenhouse gas	Symbol	Lifespan (year)	GWP time horizon	
			20 years	100 years
Carbon dioxide	CO_2	100-200	1.0	1.0
Methane (fossil)	CH_4	11.8	82.5	29.8
Methane (biogenic)	CH_4	11.8	79.7	27.0
Laughing gas	N_2O	109.0	273.0	273.0

EF: emission factor. This quantity indicates the amount of emissions (of a specific component, e.g. CO_2-eq) per functional unit (see FU).

End of Life. End of Life refers to the final stage in the life cycle of a product, when it is finally disposed of. This can take various forms: recycling, incineration, landfill, etc.

Endpoint evaluation. Endpoint evaluation is the assessment of environmental damage at the end of the impact trajectory. An endpoint assessment is mainly used in policy-supporting analyses, when no distinction is to be made between damage to humans, the environment or raw material reserves. Translating the expected potential damage at the end of the impact trajectory involves more uncertainty and is less common in supporting a sustainability trajectory.

Endpoint characterisation. Endpoint characterisation is achieved by translating the results halfway through the impact pathway into damage to one of the three areas of protection (see AoP, areas of protection).

[3] https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

Endpoint characterisation factors are used for this purpose (see characterisation). The results are endpoint indicators and are expressed as damage to human health (in terms of healthy years of life lost), damage to ecosystem quality (in terms of species lost per year), and depletion of raw materials (in terms of the cost of extracting an additional quantity of raw material).

Foreground data. Data relating to all use of materials and energy within the system boundaries of the production system under study. This concerns the quantity and nature of the materials and energy used, and the quantity and nature of the waste streams and emissions at system under study.

FU: functional unit. This is the unit output of a process (or product/service) to which the impact expressed in kg CO_2-eq (or SO_2-eq, etc.) of the process (product/service) is traced (e.g., 1 kg of dry biomass as FU gives a carbon footprint expressed in kg CO_2-eq/kg dry biomass).

GHG: Greenhouse gas. A gas that has a warming effect on the atmosphere because it reflects heat radiation. The Earth radiates heat. Most of this heat leaves the atmosphere, but some of it is reflected by greenhouse gases. Greenhouse gases act as a kind of insulating blanket around the Earth that makes life on Earth possible. This is referred to as the greenhouse effect. When this blanket of gases becomes too thick, too much heat is retained, with far-reaching consequences for the climate and global warming.

GWP: global warming potential or warming effect. The GWP indicates how strongly a particular gas retains heat in the atmosphere. This depends on the structure of the molecule, but also on its residence time in the atmosphere. By definition, the GWP of carbon dioxide (CO_2) is equal to 1. For other greenhouse gases – of which nitrous oxide (N_2O) and methane (CH_4) are the best known – the GWP is expressed in relation to CO_2. Methane retains approximately 30 times more heat than CO_2, but breaks down relatively quickly – after 12 years – compared to nitrous oxide. Nitrous oxide remains in the atmosphere for up to 109 years and retains 273 times more heat than CO_2. CO_2 breaks down after 100–200 years.

IC: Impact category. An impact category is a specific environmental problem or theme for which the contribution of human activities and the associated use of (finite) raw materials and (harmful) emissions caused to that environmental problem can be quantified. Typical impact categories related to raw material use are: land use, water use, depletion of fossil raw materials. Typical impact categories related to emissions are: climate change, ozone depletion, ecotoxicity of the aquatic environment, eutrophication of the freshwater or marine environment, etc. The abbreviations for these impact categories can be found in ANNEX 3 (§0), with a description for each IC in ANNEX 2 (§0).

IPCC: Intergovernmental Panel on Climate Change. The warming effect or GWP of greenhouse gases is constantly being reviewed by scientists. These scientists are united in an Intergovernmental Panel on Climate Change (IPCC), which regularly reports on new findings in its Assessment Reports (AR). The most recent report with the latest figures is the 6th AR, which was published in 2023 (Intergovernmental Panel on Climate Change, 2023).

LCA: Life cycle assessment. Scientific method for calculating the impact of a production process or sub-process, or of an organisation or service provided, on the environment in terms of emissions and/or use of raw materials. Emissions to soil, water and air are considered. Raw material categories include water, fossil raw materials, minerals, metals, and energy (renewable, nuclear, fossil). Emissions are quantified and their harmful effect is expressed per impact category considered (e.g. eutrophication, acidification, global warming, land use, particulate matter formation) in the corresponding equivalents. Contributions to global warming are calculated in CO_2-equivalents. Contributions to the eutrophication of freshwater environments are for instance calculated in kg P equivalents, while contributions to acidification can be expressed in mol H^+ equivalents. The system boundaries determine what is included in the calculation, ranging from only the input and output flows of a single process step (*gate to gate*) to the entire life cycle (*cradle to gate* without use phase, or *cradle to grave* with use phase and disposal phase).

LCI: Life cycle inventory or inventory. The step within an LCA in which all input and output flows of the production process under consideration are inventoried, analysed and quantified. This concerns both

background data and foreground data. This step is the most time-consuming and largely determines the accuracy and value of the results obtained.

LCIA: Life cycle impact assessment or impact calculation step. The step within an LCA in which the actual calculations are performed based on the selected impact categories and according to the selected calculation method (e.g. IPCC, EF, ReCiPe, ILCD, etc.). An LCIA produces an environmental profile: a "scorecard" of environmental impacts, such as climate change, water consumption and scarcity, land use and soil acidification. The environmental profile shows which environmental aspects score poorly in the life cycle of a product or service and which parts of the life cycle contribute most to the various environmental impacts.

Midpoint characterisation. Characterisation of environmental damage halfway through the impact pathway. Midpoint characterisation factors are used for this (see characterisation). Midpoint characterisation usually takes place at a point after which the mechanism of environmental impact is identical for all environmental flows assigned to the same impact category. E.g.: greenhouse gases cause radiative forcing in the atmosphere to varying degrees (i.e. according to their Global Warming Potential), but the effect of increased radiative forcing on the environment is the same regardless of the greenhouse gas responsible: it increases the temperature in the atmosphere, with all the harmful consequences that this entails. The indicator for climate change halfway through the impact trajectory is therefore "increase in infrared radiative forcing" and the characterisation factor is 1 kg CO_2 (into the air).

Midpoint evaluation. Midpoint evaluation is the assessment of environmental damage halfway through the impact trajectory.

PEF: Product environmental footprint. The PEF is a life cycle analysis-based methodology for determining the environmental sustainability of products. Whereas a standard LCA allows for a great deal of methodological choice, the PEF applies stricter rules that are described for each product type in the so-called category rules or guidelines per product category (e.g. guidelines for shoes, batteries, dairy products, etc.). The PEF was created by the European Commission to provide harmonised calculation rules that allow the environmental footprint of similar products to be compared within Europe. This makes PEF assessments more comparable and better suited for benchmarking products and/or services than existing LCA studies.

PEFCR: Product environmental footprint category rules. Specific guidelines for performing an environmental sustainability analysis according to the PEF method for a particular product category. Examples of existing PEFCRs are those for beer, shoes, batteries, dairy products, etc.

Single score. Comprehensive assessment of the environmental sustainability of a product or service, whereby the contributions to the individual impact categories are combined into a single score, expressed in points (μPt). This aggregation takes place after normalisation and weighting of the environmental impact scores in the various impact categories. The normalisation step involves dividing the score in an impact category by the average score for a European citizen in that impact category ("what is the average acidification impact of a European citizen?"). The weighting is done based on weighting factors that were drawn up by a broad panel of experts and citizens within the PEF method. The weighting factors of the EF method are shown in **Annex 3**.