STRAWBERRY CULTIVATION IN MOROCCO

A comparative Life Cycle Analysis and economic assessment on Macro and Nantais tunnel systems

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Abstract

This study conducts a comparative analysis of two dominant tunnel-based production systems: Macro tunnels and tunnel Nantais. Using a Life Cycle Assessment (LCA) and an Economic Assessment, the respective environmental sustainability and economic performance of strawberry cultivation in Morocco's Rabat-Salé-Kénitra and Larache (RSK+L) region is evaluated. The LCA has a cradle-to-gate approach and considers key environmental impacts such as resource use, human toxicity, and land degradation. The economic assessment measures Net Present Value (NPV), Internal Rate of Return (IRR), Return on Investment (ROI), and Payback Period (PP). The study offers region-specific insights to inform sustainable transition strategies for Moroccan policymakers, farmers, and industry actors.

Findings reveal a clear trade-off between environmental impact and profitability. The Macro tunnel system generates higher absolute profits due to superior access to the high-value fresh export market, but has higher environmental impacts. In contrast, the tunnel Nantais system demonstrates lower material requirements and reduced environmental impacts, while remaining financially viable due to lower initial investment costs. Sensitivity analysis identifies yield and fresh market access as the primary drivers of economic success in both systems. The results also show a social trade-off: high investment barriers can exclude farmers from accessing the more profitable Macro system, highlighting the structural inequality in the region's strawberry cultivation sector.

Improving on-farm efficiency, particularly in irrigation, fertiliser, and pesticide use, is essential to reduce material waste and land depletion. Policymakers should also address structural inequalities that limit farmers from accessing high-value markets associated with Macro tunnel system strawberry cultivation. Last, operational cost structures should be disaggregated, and real-world data on yield performance and blue water use, and its distinction between the two systems should be measured to increase representativeness of farming data.

Keywords: Life Cycle Assessment, strawberry cultivation, Morocco, Macro tunnel, tunnel Nantais, environmental impact, economic analysis, trade-offs

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1. Introduction

1.1. Background

Morocco's horticulture has become increasingly important for the country, cultivating a total area of 40.000 hectares and a total production of two million metric tons in 2022 (Ministerie van Landbouw, Visserij, Voedselzekerheid en Natuur, 2025). Together with fishing and forestry, horticulture accounts for 15–20% of the country's national GDP and employs approximately 45% of the workforce (International Trade Administration, 2024).

Of all the regions in Morocco, Rabat-Salé-Kénitra and Larache (RSK+L) contributes the most to the national Agricultural GDP (Figure 1). It is also one of the most important areas for fresh fruit and vegetable production, amounting to 73.000 tons yearly (Hubers & Kroesen). However, the intensive cultivation practices, in combination with drip-irrigation use, have caused extensive groundwater depletion. Moreover, the region has already faced droughts and increasing freshwater scarcity in the last decade (TRT Global, 2025). Although the Souss Massa region in the south of the country has faced the strongest freshwater pressures of all regions, the RSK+L region is expected to receive similar problems in the near future (Hubers & Kroesen, 2024).

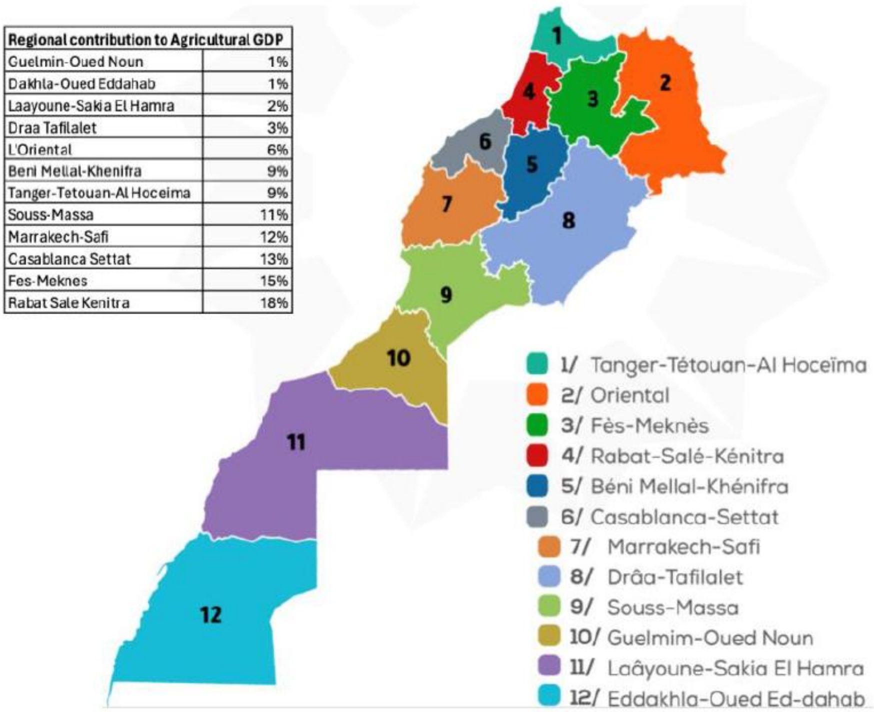

Figure 1. Regional contribution to Agricultural GDP (Hubers & Kroesen, 2024).

To address these problems, the Moroccan government introduced the Green Morocco Plan (2010–2020) and the Generation Green Plan (2020–2030). The policies improved export-oriented agriculture and strengthened economic growth, with over 40% of Morocco's total agricultural output being exported, 63% of which is exclusively for the European Union (Hubers & Kroesen, 2024). However, critics claim that Morocco aggravates its freshwater scarcity because of this export-oriented economy (Collas, 2023). Furthermore, Morocco has been criticised for not addressing long-term sustainability problems enough (Hubers & Kroesen, 2024).

Within the RSK+L region, Strawberries are the most widely grown crop, with over half of the total horticulture area being devoted to them (Aschehoug, 2022). The area is convenient for red fruit cultivation due to its mild, humid Mediterranean climate, access to fertile soils, and accessibility to key water sources like the Loukkos and Sebou river basins (Hipeca, 2024; Motib, 2020). Additionally, its coastal positioning reduces the risk of frost damage, making it especially suited for berry cultivation. Strawberries are primarily produced in open-field tunnel-based systems, using either Macro tunnels, tunnel Nantais, or a combination of both, see Figure 2 (Messem, 2025).

Strawberry cultivation gets increased attention however, as strawberries are a water-intensive crop, ranking second only to watermelon in terms of water requirements (Whitebread, 2024). While drip irrigation has become the main use of water input to cultivate strawberries in the region, its application has not always been efficient. Combined with inefficient use of fertilisers and pesticides, these practises have contributed to hydrological stress and changed groundwater recharge patterns in the agricultural region (Hatfield, 2014; Messem, 2025).

Figure 2. Macro tunnel (left) and tunnel Nantais (right) (Author, 2025).

1.2. Literature Review and Research focus

Considering the above challenges, the Moroccan government hopes to reduce the environmental footprint of strawberry horticulture while protecting national food security and maintaining the sector's economic competitiveness. Yet, the exact environmental impacts and economic performances of the two tunnel systems in the region remain unknown. Although Macro tunnels tend to give higher yields for strawberries in Morocco (Yara, 2018; Haifa-group, n.d.), productivity has not been directly compared with tunnel Nantais, nor has the productivity been measured in the RSK+L region specifically. On the other hand, Menzel (2025) measures similar yields for low and big tunnels, mainly due to maintaining a high temperature. Although environmental impact of strawberry production has been studied on Spain (Romero-Gámez & Suárez-Rey, 2020b) and Iran (Khoshnevisan et al., 2013), no comparative environmental assessment has been conducted on strawberry farming in Morocco. Pergola et al. (2023) did combine an environmental and economic analysis on open field, tunnel strawberry cultivation, but was located in southern Italy, and trade-offs between environmental impact and economic performance are explicitly mentioned. General export numbers of the RSK+L region and Moroccan national export market exist (International Trade Organization, 2024; Aschehoug, 2022; EastFruit, 2023). However, little is known about the on-farm economic performance of different cultivation systems at the regional level.

To educate farmers, investors and policy makers in the RSK+L region about the environmental impact and economic performance of strawberry cultivation through Macro and Nantais tunnel systems, a comparative study of the systems is essential. This study intends to provide insight into the current functioning of the two tunnel-based strawberry cultivation systems in the RSK+L region. To do this, the following research question is formed:

"What are the environmental and economic trade-offs between Macro tunnel and tunnel Nantais systems in strawberry farming in Morocco's RSK+L region?"

To address the main research objective, the following sub questions are formulated:

1. What are the environmental impacts of Macro tunnel and tunnel Nantais systems used in strawberry cultivation in the RSK+L region?
2. What are environmental hotspots in both tunnel systems?
3. How do the Macro tunnel and tunnel Nantais systems compare in terms of yield productivity and blue water footprint in the RSK+L region?

4. How does the economic performance of the Macro tunnel system compare to that of the tunnel Nantais system, based on key indicators such as NPV, IRR, ROI, and Payback Period?
5. Which system parameters influence the economic performance of each tunnel system and to what extent?

2. Methodology – Environmental Analysis

To compare the environmental impacts of Macro tunnel farming and tunnel Nantais farming in the RSK+L region, a comparative Life Cycle Assessment (LCA) is carried out. It is conducted according to the "Handbook on life cycle assessment" by Guinée et al. (2002), which functions as a guide to the ISO standards. ISO 14040 defines LCA as "a compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (Guinée et al., 2002). This makes LCA an appropriate tool to analyse the environmental performance of production systems like strawberry farming, since they have a clear function, producing strawberries. Furthermore, LCA helps to identify where in the cultivation process the main impacts are produced. Knowing this, strategies can be designed to effectively tackle the main environmental hotspots of a product.

The Life Cycle Assessment (LCA) method follows a standardised structure of four phases, as described in ISO 14040: defining the goal and scope, collecting the inventory, assessing the impacts, and interpreting the results, see Figure 3. The first phase explains the aim of the study, the functional unit, and who the results are for. In the inventory phase, the system is described in detail and the necessary data is collected. This phase ends with a list of all the inputs and outputs between the system and the environment, such as emissions and resource use. In the impact assessment phase, the inventory data is translated into environmental impact scores using specific factors. These impacts can include categories like climate change, acidification of soil, or marine pollution. The final phase, interpretation, involves analysing the results to identify the most impactful processes and drawing conclusions or making suggestions for improvement.

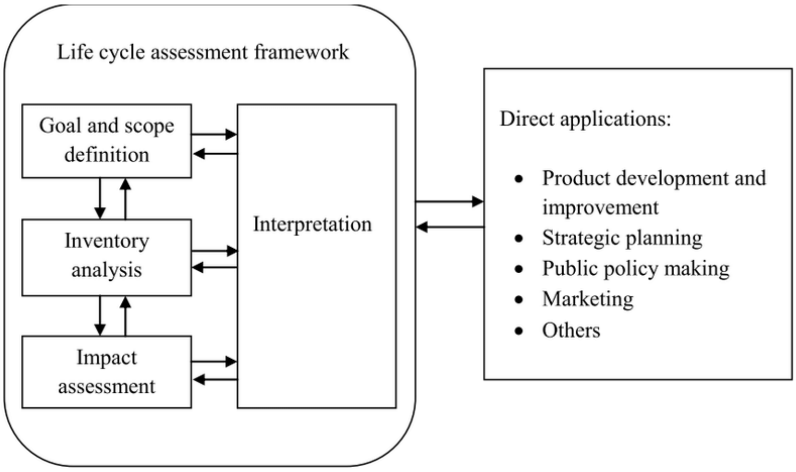

Figure 3. Framework and phases of LCA. (ISO 14040:2006, 2022).

2.1. Goal and scope definition of LCA

2.1.1. Goal definition

The goal of this LCA is to compare the environmental impacts between Macro tunnel strawberry production and tunnel Nantais strawberry production, and to find the hotspots in the production processes. Findings and insights can be communicated to farmers, investors and policy makers in the RSK+L region, and LDE's network in Morocco. The study is conducted by a MSc student Industrial Ecology at Leiden University and Technical University Delft (joint degree).

2.1.2. Scope definition

This study will perform two cradle-to-gate LCAs in line with the ISO 14044 and the LCA handbook by Guinée et al. (2002). It focuses on the current production systems of 1) Macro tunnel and 2) tunnel Nantais strawberry production. The total size of the study is five months, conducted in 2025.

Generally, LCAs cover the entire life cycle of a product system; from the extraction of resources, through the production of materials, the use phase and its end-of-life (EoL), either through reuse, recycling, landfilling or other treatment (Guinée et al., 2002). This is called a cradle-to-grave approach. However, in this specific context, the LCA aims to compare the environmental sustainability of the cultivation technologies themselves, covering the processes from seedling to the point of harvest (gate). A limitation of this is that EoL impacts can differ between the two systems. Macro tunnels require more plastic and steel materials which, depending on waste management practices, can lead to higher emissions and environmental impacts. However, due to limitations in data availability and time constraints, it was not feasible to conduct a cradle-to-grave assessment. For this reason, this study applies a cradle-to-gate approach. Nevertheless, Macro contains more materials than Nantais. Because of this, it is expected that Macro will have a greater environmental impact, even when EoL phases are considered. Moreover, the entire production process of strawberry cultivation is taken into account, including its hotspots. Thus, although the cradle-to-gate scope is a limitation, it does not compromise the validity of the results.

2.1.3. Functions of the system

Function

Cultivating strawberries

Functional unit

1 kilogram of strawberries cultivated

Alternatives

1. Macro tunnel strawberry cultivation
2. Tunnel Nantais strawberry cultivation

Reference flows

1. 1 kilogram of strawberries cultivated by Macro tunnel
2. 1 kilogram of strawberries cultivated by tunnel Nantais

2.2. Inventory analysis

2.2.1. System boundaries

The product system of the LCA includes all foreground processes (modelled by author) and background processes (in the Ecoinvent database) required to produce the reference flow: 1 kilogram of strawberries cultivated. One foreground process is modelled for each of the systems: strawberry production. This requires a lot of inputs and outputs, coming from background processes. Relevant background processes are strawberry seedling production, diesel production – burned in agriculture, liquefied petroleum gas production, and production of packaging – for fertilisers. Transportation impacts are also included, based on mass and distance. Distances are calculated using Google Maps and measured to Kenitra, as most of the farms are located around it (Messem, 2025). The calculations of distances, along with a detailed inventory of all processes including flows, value, unit, and geographical specification are provided in Appendix B (Macro) and Appendix C (Nantais). The results of the Life Cycle Assessment are presented in Chapter 3.

2.2.2. Cut-offs

In principle, a Life Cycle Assessment (LCA) aims to account for all processes involved in the life cycle of a given system. In practice, however, this is rarely feasible, and system boundaries must be defined using cut-off criteria (Guinée et al., 2002). Certain processes, flows, or impacts are therefore excluded from the assessment, typically due to limitations in data availability, time, or financial resources (Guinée et al., 2002). The following flows are excluded from the system boundary due to several reasons:

Strawberry Plant residu: no representative product exists in the Ecoinvent database for strawberry plant biomass left in the field. Since the residue is of organic origen, and it is mainly left to decompose naturally (Messem, 2025), its environmental burden is expected to be minimal.

Pest control: no detailed data were available in Ecoinvent databases for the specific pest control methods applied in the studied systems.

- Biological pest control (bees, bumblebees):
- Non-biological pest control (sticky traps)

Organic fertiliser (algi-extract): no data available in Ecoinvent databases. However, due to relative low quantities and its organic origin, low impact is expected.

Labour-related processes: Due to time constraints, no primary or secondary data were collected regarding environmental impacts associated with labour. This includes inputs such as clothing, transport to work, and food consumption.

Microplastic leakage during the production cycle: This does exclude plastic waste after the production cycle, but solely during the growing process. This is excluded due to time constraints on primary and secondary data research. It consists of plastic mulch and plastic film losses.

2.2.3. Inventory Data

All processes and data collection are modelled in the Life Cycle Assessment software openLCA (openLCA, n.d.). After this, the inventory results are calculated, which considers all related products and their values, required to create the reference flow: 1 kilogram of strawberries cultivated. The inventory results are discussed in chapter 5.1.

2.2.4. Case study and data collection

This study conducts a comparative case study of two representative open-field strawberry production systems in the RSK+L region in Morocco. Strawberries were selected as the reference crop because they are the most grown crop in the region. In addition, strawberries are Moroco's second-most exported horticultural product and are strongly associated with water- and input-intensive production practices, making them highly relevant for assessing the environmental and economic sustainability.

The first system uses Macro tunnels, which resemble larger greenhouse-like structures (Gonvarri Agrotech, 2024), while tunnel Nantais uses lower, lighter structures and are more economic to install (Schoubs, 2023). Due to data limitations, differences in farm size are not considered in the analysis, which is a limit of this study. Future research should account for differences in farm size, as this factor may influence productivity and material efficiency, affecting the environmental and economic performance.

Two data types are used. First, secondary data is gathered from Moroccan specific horticulture and, when necessary, global horticulture. Key references include Hubers & Kroesen (2024), who evaluated the Green Morocco Plan and the Generation Green, commissioned by the Netherlands Enterprise Agency. Additionally, all upstream inventory (background processes) is taken from the Ecoinvent 3.9.1 database, which covers region-specific inputs such as diesel specified for agricultural machinery, drip-irrigation infrastructure specific to Moroccan conditions, packaging materials for fertilisers and pesticides, and imported strawberry seedlings form Spain (Ecoinvent, 2025). Where possible, country-specific data was chosen. However, this was only feasible for the processes 'irrigation' and 'strawberry seedling planting'. All other processes and flows, such as nitrogen fertiliser, low-alloy steel and zinc production, are global datasets representing the Moroccan values for the case study. When the origin of a product is unclear, global locations are used.

Second, primary data was collected during fieldwork conducted in collaboration with the Leiden-Delft-Erasmus (LDE) Thesis Lab in the RSK+L region. This data was mainly provided by Messem (2025), a commercial strawberry processer operating in the RSK+L region. A more elaborate description of Messem is given in Appendix A. The decision to use a single data source was driven by a lack of comparable data from other farms in the region and the limited duration of the fieldwork period. According to Hubers and Kroesen (2024), Messem has an annual production of 18,000 tonnes of red fruits. This means that Messem represents a quarter of the region's total annual production of 73,000 tons of red fruits.

Moreover, Messem's growers consist of both small- and large-scale farms (with less than or more than five hectares of land). This diverse data input increases the representativeness of the dataset by capturing production realities across a broader range of farm sizes. However, the exact proportion of small and large farms within Messem's supply is unknown. Consequently, the extent to which this dataset reflects the entire regional farming structure cannot be verified. Furthermore, since Messem's data does not distinguish farm size, it is unsure if this has an influence on environmental impact or economic performance, limiting this study. Despite these limitations, conducting this research provides valuable initial insights into the environmental and economic trade-offs of tunnel-based strawberry farming in the region. It provides a foundation for future research based on more representative and disaggregated data.

2.3. Impact Assessment

2.3.1. Impact categories

The Life Cycle Impact Assessment is the phase where the Inventory Analysis is further processed and interpreted in terms of environmental impacts and societal preferences (Guinée et al., 2002). To do this, a list of impact categories is defined. The categories are taken from the impact method family 'Ecoinvent Environmental Footprint (EF) v3.0'. EF is mid-point based, which means that it evaluates specific environmental issues (e.g. climate change, eutrophication and acidification) that arise along the chain of cause and effect between emissions and result. End-point focusses more on the impacts from the issues but are not comprehensive enough according to Guinée et al. (2002, p.63). Midpoint indicators on the other hand are more scientifically robust and involve less uncertainty. EF specifically is recommended by Guinée et al. (2002), and it is the method maintained by the European Commission (Ecoinvent, 2024).

Table 1 provides an overview of all 16 impact categories considered by EF v3.0, as presented by Sanyé-Mengual et al. (2022b). Table 2 gives an explanation what each category entails. Although climate change, ecotoxicity, freshwater and human toxicity are aggregated in the table, they are considered individually in the study. The full names, units, and values of the impact categories can be found in Appendix G.

Table 1. Environmental Footprint v3.0. Impact categories overview.

Impact Category	Indicator	Characterisation Factor	Unit	Key References (Impact Assessment Model)
Acidification	Accumulated Exceedance	AC	mol H^+ eq	Seppälä et al. (2006); Posch et al. (2008); Goedkoop et al. (2013)

Impact Category	Indicator	Characterisation Factor	Unit	Key References (Impact Assessment Model)
Climate change	Radiative forcing	CC	kg CO_2 eq	Intergovernmental Panel on Climate Change (IPCC, 2013)
Ecotoxicity, freshwater	Comparative Toxic Unit	ECOTOX	CTUe	Based on USEtox2.1 model (Fantke et al., 2017), adapted as in Saouter et al. (2018)
Eutrophication, freshwater	Nutrient enrichment	FEU	kg P eq	Struijs et al. (2009), as applied in ReCiPe 2008 (Goedkoop et al., 2013)
Eutrophication, marine	Nutrient enrichment	MEU	kg N eq	Struijs et al. (2009), as applied in ReCiPe 2008 (Goedkoop et al., 2013)
Eutrophication, terrestrial	Accumulated Exceedance	TEU	mol N eq	Seppälä et al. (2006); Posch et al. (2008); Goedkoop et al. (2013)
Human toxicity, cancer	Comparative Toxic Unit	HTOX_c	CTUh	Based on USEtox2.1 model (Fantke et al., 2017), adapted as in Saouter et al. (2018)
Human toxicity, non-cancer	Comparative Toxic Unit	HTOX_nc	CTUh	Based on USEtox2.1 model (Fantke et al., 2017), adapted as in Saouter et al. (2018)
Ionising radiation, human health	Human exposure efficiency	IR	kBq U^{235} eq	Frischknecht et al. (2000), as developed by Dreicer et al. (1995)
Land use	Soil quality index	LU	pt	De Laurentiis et al. (2019); Horn and Meier

Impact Category	Indicator	Characterisation Factor	Unit	Key References (Impact Assessment Model)
				(2018), based on LANCA model
Ozone depletion	Ozone depletion potential	ODP	kg CFC-11 eq	World Meteorological Organization (WMO, 2014)
Particulate matter formation	Disease incidence	PM	disease incidences	Fantke et al. (2016); UNEP (2016)
Photochemical ozone formation	Tropospheric ozone formation potential	POF	kg NMVOC eq	Van Zelm et al. (2008), as applied in ReCiPe 2008 (Goedkoop et al., 2013)
Resource use, fossils	Surplus cost potential	FRD	MJ	van Oers et al. (2002)
Resource use, minerals and metals	Surplus cost potential	MRD	kg Sb eq	van Oers et al. (2002)
Water use	Available Water Remaining (AWARE)	WU	m^3 water eq	Boulay et al. (2018); UNEP (2016)

Table 2. Environmental Footprint v3.0. Impact categories explanation.

Impact Category	What does it measure?	Why is this important?
Acidification	Emissions that cause acidification of soils and water bodies (e.g., SO_2, NO_x)	Acidification can damage forests, crops, aquatic life, and buildings

Impact Category	What does it measure?	Why is this important?
Climate Change (GWP100)	Emissions of greenhouse gases contributing to global warming, measured in CO_2-equivalents	Climate change affects global temperature, weather patterns, sea level rise, and biodiversity
Ecotoxicity: freshwater	Overall toxicity to freshwater ecosystems caused by chemical emissions	Ecotoxicity reduces biodiversity and affects the health of aquatic ecosystems
Eutrophication: freshwater	Enrichment of freshwater bodies with phosphorus, leading to algal blooms and oxygen depletion	Freshwater eutrophication leads to fish kills, biodiversity loss, and water treatment issues
Eutrophication: marine	Nitrogen enrichment of marine environments, causing dead zones and biodiversity loss	Marine eutrophication disrupts food chains and leads to large-scale hypoxic zones
Eutrophication: terrestrial	Nitrogen deposition on land ecosystems, altering soil chemistry and vegetation patterns	Terrestrial eutrophication impacts plant diversity and soil microbial communities
Human Toxicity: non-carcinogenic	Potential harm to human health from non-carcinogenic toxic substances	Chronic exposure to non-carcinogens affects organs, development, and overall health
Ionising Radiation: human health	Exposure to ionising radiation that can affect human health (e.g., from nuclear energy use)	Radiation exposure can increase cancer risk and cause genetic damage
Land Use	Impacts of land occupation and transformation on soil quality and ecosystem services	Land use alters habitats, reduces carbon storage, and increases erosion
Ozone Depletion	Depletion of the ozone layer due to emissions of substances like CFCs	Ozone depletion increases UV radiation exposure, leading to skin cancer and crop damage

Impact Category	What does it measure?	Why is this important?
Particulate Matter Formation	Emissions of fine particles and precursors that affect air quality and human respiratory health	Particulate matter causes cardiovascular and respiratory diseases
Photochemical Ozone Formation	Emissions of VOCs and NO_x that form ground-level ozone (smog), harming health and crops	Ground-level ozone harms human health and reduces agricultural yields
Resource use: fossils	Use of fossil energy resources like coal, oil, and natural gas	Fossil resources are non-renewable and their extraction and use cause environmental degradation
Resource use, minerals and metals	Use of mineral and metal resources (e.g., copper, zinc, rare earths)	Mineral depletion can lead to resource scarcity and ecosystem damage from mining activities
Water Use	Freshwater consumption leading to scarcity, particularly relevant in water-stressed regions	Overuse of water affects regional water security and ecosystem sustainability

2.3.2. Classification

In this obligatory classification step in LCA, the results of the Inventory are systematically assigned to the relevant environmental impact categories (Guinée et al., 2002). For instance, emissions as carbon dioxide (CO_2) and methane (CH_4) are categorised under climate change due to their contribution to global warming. This process ensures that different flows are translated into environmental effects. The classification is based on EF v3.0.

2.3.3. Characterisation, normalisation, and contribution analysis

In the characterisation step, the collected life cycle inventory data for both tunnel systems is translated into midpoint environmental impacts using category-specific characterisation factors. This results in a detailed environmental profile for each system. For comparison, the scores are first scaled to illustrate which system performs better across each category. After this, the results are normalised, meaning each characterisation score is divided by a reference value that represents the total environmental burden of a larger reference system (Crenna et al., 2019). This study applies the standard EF v3.0 normalisation set: the World (2010) reference values. Normalisation is done to "better understand the relative importance and magnitude of the results" for each alternative (Guinée et al., 2002, p. 90). This step is recommended for any LCA, as it helps identify which impact categories are most significant for the studied system. Last, a contribution analysis is conducted to calculate the overall contribution to the highest scoring categories from the normalisation results. In the contribution analysis, the impact is traced back to the process or environmental factor that caused it. These 'hotspots' show where the biggest percentage of impact lies, enabling more targeted interventions. A visualisation of the steps is shown in Figure 4.

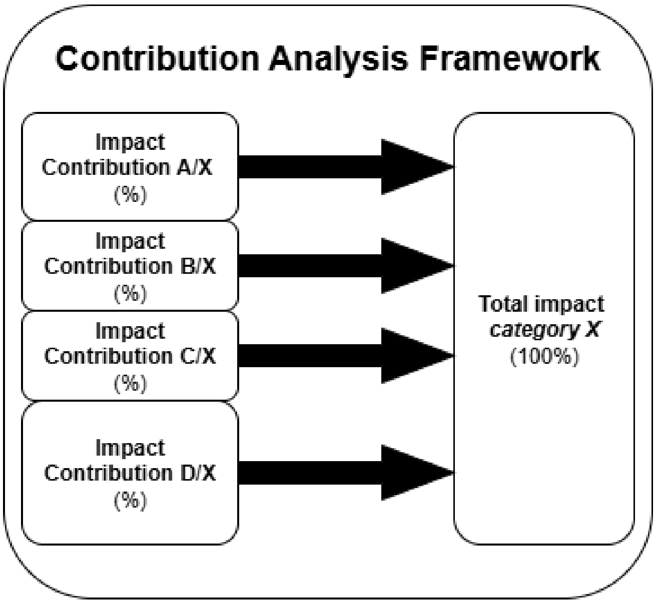

Figure 4. Visualisation of Contribution Analysis (Author, 2025).

2.3.4. Sensitivity analysis

In LCA it is essential to assess the influence of methodological choices on results, such as the selection of impact assessment method families. (Guinée et al., 2002). Impact assessment methodologies show variability regarding their scientific models and value choices. Consequently, the implementation of alternative methods increases the robustness of results. Therefore, as a sensitivity analysis, the characterisation results of the systems are calculated again. Apart from EF v3.0, Ecoinvent has ReCiPe 2016 v1.03 and CMLV4.8 2016 as method families. ReCiPe combines both midpoint and endpoint modeling and it allows for broader interpretability than EF v3.0. By comparing EF and

ReCiPe results for the same life cycle inventory, this analysis explores how resilient the conclusions are across the model and helps identify categories that are sensitive to the choice of impact method. Both families are mid-point directed, but ReCiPe has a total of 1409 characterisation factors, whereas CML has 800 (Romojaro-Pérez, 2023). For this reason, ReCiPe 2016 v1.03 is chosen for sensitivity analysis. The downside of this is that for most impact categories, both ReCiPe and CML use different units, making them incomparable. Only four impact categories are directly comparable in their characterisation results: climate change – global warming potential (GWP100), eutrophication: freshwater – fraction of nutrients reaching freshwater end compartment (P), eutrophication: marine - fraction of nutrients reaching marine end compartment (N), and ozone depletion - ozone depletion potential (ODP). The lack of comparable categories limits the robustness of the results.

3. Methodology – Productivity and Water Use

3.1. Productivity

When comparing two agricultural systems, productivity (yield; y) plays an important role. The higher the yield, the more strawberries a farmer can sell to the export or internal market. The productivity of the Macro and Nantais strawberry cultivation systems is measured and compared by the yields, in ton strawberry output per hectare of farming [ton/ha]. The productivity data is provided by Messem (2025), being 40 tons of strawberry output per hectare per year. However, it is unclear if this number is trustworthy. As stated in the introduction, some literature claims Macro tunnels give higher yields for strawberries in Morocco (Yara, 2018; Haifa-group, n.d.). Other literature states that similar yields for low and big tunnels are measured (Menzel, 2025). Due to limited access to detailed data, the yield for both tunnel systems is set as a base level of 40 tons/ha. The sensitivity results of yield on the economic performance are shown in chapter 6.2.

3.2. Water footprint

With RSK+L experiencing serious freshwater scarcities, it is insightful to inspect the water use in both systems. According to Messem (2025), roughly the same amount of water is used in both tunnel systems, being 7000 cubic meters per hectare. With a yield of 40 tons/ha, this comes down to 175 litres of water per kilogram of strawberry output. The water footprint calculation can be found in Appendix E. Although it is unlikely that on average both systems use precisely the same amount of water, lack of access to more precise data obliges this study to include 175 L/kg drip irrigation for both systems. It is highly recommended that the exact water use for both systems is measured during the whole cultivation cycle in the region.

Mainly pumped groundwater is used with drip irrigation for the cultivation, where surface water produced by dams are too low of quality for farming (Messem, 2025). The actual groundwater-to-surface water ratio is unclear, so the Ecoinvent background process 'irrigation, drip' dataset with geographical scope of Morocco (MA) is used in the LCA. The dataset does not only include the total amount of water used, but it also considers the water pumping of ground water and surface water, as well as the infrastructure and energy use, but it excludes water evaporation or infiltration (ecoQuery, 2017).

The efficiency of the drip irrigation dataset is 90%, which is likely too high compared to reality in the region (Messem, 2025). This means that the environmental impact of irrigation is slightly underestimated. However, considering the dataset is Morocco-specific and covers a large part of the irrigation system, this dataset is the most suitable available option for modelling within the scope of this study.

4. Methodology – Economic Analysis

To evaluate the financial attractiveness of strawberry production in the RSK+L region, this chapter analyses the economic performance of Macro tunnel and tunnel Nantais cultivation.

4.1. Economic indicators

The economic performance is evaluated by four indicators, according to FAO's "financial analysis in agricultural project preparation" (Selvavinayagam, 1991). The indicators are: Net present value (NPV), Internal Rate of Return (IRR), Payback Period (PP), and Return on Investment (ROI).

According to Kiropoulos (2019), calculating NPV is a basic rule for making financial decisions. The NPV measures the total value of future profits, adjusted for the time value of money and expressed in today's terms. A higher NPV indicates a more economically attractive investment. First, the annual net cash flow per hectare (P) is calculated as total income (I) minus total costs (C).

$$(1)\ P = I - C$$

Each annual cash flow is then discounted to its future value using a discount rate r. The discount rate shows how much society prefers current income over future income. For this study it is set to a base rate of 10%, based on market estimations discussed in

Moore (2023). A time span of 10 years is taken according to Selvavinayagam (1991). The sum of all discounted annual cash flows minus the initial investment C_0 then gives the NPV:

$$(2)\ NPV = \sum_{t=1}^{n} \frac{P}{(1+r)^t} - C_0$$

P represents the net cash flow per hectare in year t. C_0 shows the initial investment and is extracted from the PV, n is the number of years in the investment, and r the discount rate.

Next, IRR demonstrates the potential return of an investment, with a higher IRR indicating better performance. It measures annual growth rate, by setting the NPV at zero, meaning that every positive return is a healthy investment. This creates the following formula (6), where the 0 represents the NPV value, and IRR is calculated.

$$(3)\ 0 = \sum_{t=1}^{n} \frac{P}{(1+IRR)^t}$$

The third indicator ROI measures how much return is generated relative to the initial investment. It is calculated by dividing the total net profit over the investment period by the initial investment:

$$(4)\ ROI = \frac{\sum_{t=1}^{n} P}{C_0}$$

Last, PP shows the amount of years required to recover the initial investment. It is calculated by dividing the initial investment by the annual net cash flow. Important to note is that this PP formula assumes constant yearly profits. If variable annual returns are relevant, cumulative cash flow analysis is required (Selvavinayagam, 1991). This study assumes fixed annual values for income, costs, and yield across the 10-year period. This creates the following formula (7):

$$(5)\ PP = \frac{C_0}{P}$$

NPV and IRR are calculated using Excel's built-in financial functions, while ROI and PP are calculated manually. The detailed calculations and values used are provided in Appendix E, the results of the economic assessment are shown in chapter 6. All numerical results are presented using the European convention, where a period (.)

separates thousands and a comma (,) reflects decimal values (e.g., 1.000 = one thousand; 0,5 = zero point five).

4.2. Sensitivity Analysis

Just as with the environmental assessment, a sensitivity analysis also performed on the economic assessment to examine how robust the baseline results are with respect to the chosen economic indicators. The analysis evaluates four key variables, each tested at three different values to observe the effect on NPV, IRR, ROI and PP.

The first variable is the percentage of strawberry yield sold to the fresh market. Since the average price for fresh-market strawberries is nearly three times higher than for the non-fresh or processed market, this share has a major influence on total farm revenue (Messem, 2025). The proportion sold to the fresh market can vary due to changes in strawberry quality, pest or disease pressure, or fluctuations in market demand, making it an important factor to include.

The second variable is yield per hectare, which has a direct and substantial effect on farm income. As the main productivity measure, it determines the volume of strawberries available for sale and strongly impacts all four economic indicators. Yield variability can be caused by factors such as drought, pests, climate variability, or soil degradation, all of which are increasingly relevant in the region.

The third variable is the discount rate. Among the four indicators, it only influences the NPV, but does this strongly (Moore, 2023). As the discount rate reflects how future income is valued relative to present income, incorporating it into the sensitivity analysis allows for a better understanding of how economic assumptions affect long-term profitability (Moore, 2023).

The fourth variable considers subsidies for drip irrigation. Under the Green Morocco Plan, the Moroccan government subsidised 80–100% of the cost of drip irrigation systems for farmers between 2010 and 2020 (Hubers & Kroesen, 2024; Messem, 2025). However, the subsidy was generally granted only once, even though many farmers replace irrigation pipes and plastic tubing annually (Messem, 2025). After 2020, these subsidies were stopped under the Generation Green Plan. Including this variable helps assess the degree to which such subsidies influence long-term economic performance.

Appendix D and E give a clear overview on the values of the variables, and the reasoning behind the chosen values.

5. Results – Environmental Assessment (LCA)

This chapter presents the results of the environmental assessment of the two strawberry cultivation systems studied in the RSK+L region: Macro tunnel and tunnel Nantais. The chapter is structured as follows: first, the life cycle inventory results are discussed, highlighting relevant material and water flows. Next, the environmental impacts are assessed, including the characterisation and normalisation results. Then, a contribution analysis is conducted, identifying the key processes responsible for the highest environmental impacts. Lastly, a sensitivity analysis is conducted by comparing two impact method families, evaluating the robustness of the results.

5.1. Inventory Analysis Results

The Macro system scores higher on all *inputs* than the Nantais system. To produce one kg of strawberries, the Macro tunnel requires 0,018 megajoules (MJ) of geothermal energy, whereas the tunnel Nantais requires 0,0057 MJ, more than double the amount. The same applies to biomass energy (gross calorific value): Macro requires an input of 0,0029 MJ, whereas the Nantais system requires 0,0013 MJ. Macro also requires more zinc, which is mainly used for coating steel structures. It requires 0,015 kg, whereas the Nantais system requires 0,00090 kg. More hard Coal is also used, with 0,55 kg for macro and 0,16 kg for Nantais. Regarding the outputs, it is unclear whether the Macro system only scores higher, given that there are 1.936 flows, which is too many to assess. However, some flows stand out: Macro emits three times more fossil carbon dioxide (0,67 kg versus 0,23 kg) and three times more non-fossil Carbon dioxide (0,0033 kg versus 0,0011 kg). Additionally, the Macro system emits more than four times as much nitrate into water/surface water (2,7E-04 kg versus 6,4E-05 kg), which is one of the main causes of agricultural water pollution (European Commission, n.d.).

A full overview of the inventory results can be found in Appendix F. Given Morocco's water stress, the usage of freshwater in both systems relevant for this study. Table 3 shows the quantities of water from various required to produce 1 kilogram of strawberries. The Macro tunnel system requires more for all types of inputs, reaching to more than five and four times more for water with unspecified natural origin. This water does not come from direct use in cultivation but is required over the entire life cycle of strawberry production.

Table 3. Life cycle inventory water flows inputs.

Name	Macro tunnel inputs	Tunnel Nantais inputs	Unit	Relative Difference

Water, unspecified natural origin	0,01612	0,00289	m3	**5,58**
Water, unspecified natural origin	0,00535	0,00128	m3	**4,18**
Water, turbine use, unspecified natural origin	9,426	2,604	m3	**3,62**
Water, cooling, unspecified natural origin	0,07256	0,02338	m3	**3,10**

Water use is not the only key result. The use of iron also shows differences between the two system: 0,56 kg for Macro and 0,14 kg. This aligns with the steel data collection in Appendix A. Iron is particularly relevant because it is the main component of steel, a material widely used for structural elements in both the Macro and Nantais tunnels. Since steel is approximately 97% iron, iron serves as a reliable indicator of the material intensity of both systems (OneMonroe, 2019).

Next, the inventory results will be interpreted in terms of environmental impact categories.

5.2. Impact Assessment results

5.2.1. Characterization results

The characterisation results are scaled to the Macro tunnel system, which is set at 100% for each impact category. This is done, so that the tunnel Nantais results are expressed as a relative percentage of the Macro impact, which allows for direct comparison between systems across the categories. A complete overview of these scores can be found in Appendix G.

Figure 5 shows the Macro tunnel system has a higher impact than the tunnel Nantais system on all impact categories, except for land use – soil quality index, where both systems contribute equally. The other categories show similar ratio between Macro and Nantais. On average, the tunnel Nantais system scores approximately 28% of the environmental impact of the Macro tunnel system across all impact categories.

Next, as discussed in chapter 2.3.1, the characterisation results are normalised to find the most significant impact categories to the product system of strawberry cultivation.

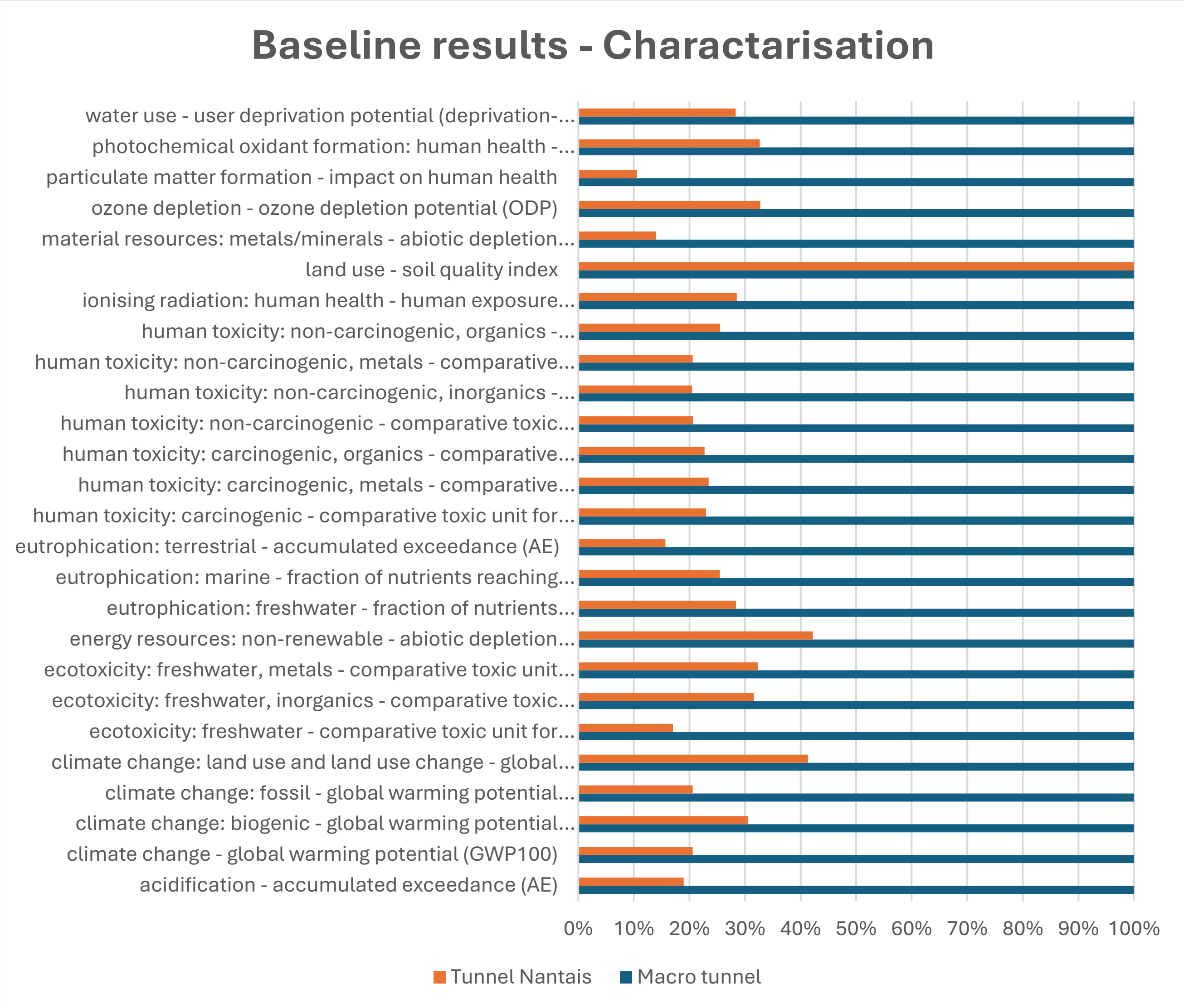

Figure 5. Baseline characterisation results.

5.2.2. Normalisation results

Figures 6 and 7 present the normalised environmental impact results for both tunnel systems. The units are presented in Figure 8, where all categories have different units. In these visualisations, the subcategories of ecotoxicity and human toxicity are aggregated to reflect the total impact within each category respectively. Several impact categories have a normalised score of zero, which indicates insignificance to the overall environmental impact. For clarity, these categories are excluded from the graphs, but they are reported in Appendix H, alongside the complete set of normalised values.

Among all impact categories, land use – soil quality dominates the results, with a score more than 200 times higher than the second-highest category. Both systems contribute equally to this impact, each with a value of 0.612 m2*yr. Other relatively high-scoring categories are freshwater ecotoxicity, particulate matter formation, human toxicity (carcinogenic), and material resources (metals and minerals).

An issue arises in the subcategory ecotoxicity freshwater (organics), which shows a negative characterisation score; an outcome that is not physically meaningful (Rosenbaum et al., 2008, p.441. As a result, the total score for freshwater ecotoxicity is underestimated, and the actual impact is likely higher than what is shown in Figure 6. Due to the presence of this invalid sub-score, the category could not be reliably included, as the source of the flows cannot be accurately identified. A detailed explanation on how to this value should be interpreted is provided in Appendix G.

As the other four categories are the most significant contributors to the total LCA results, they will be analysed further in the Contribution Analysis in the next chapter.

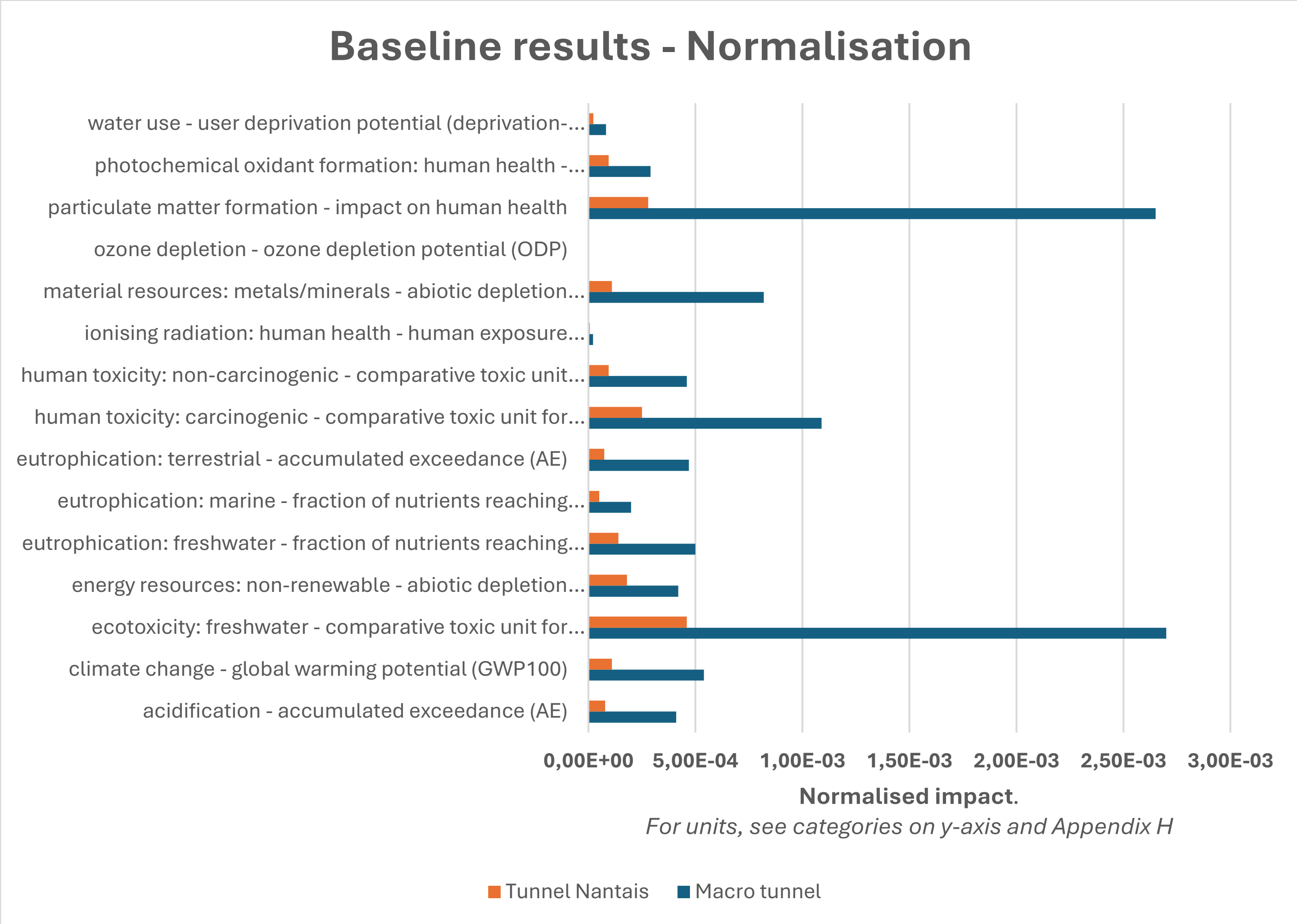

Figure 6. Baseline normalisation results.

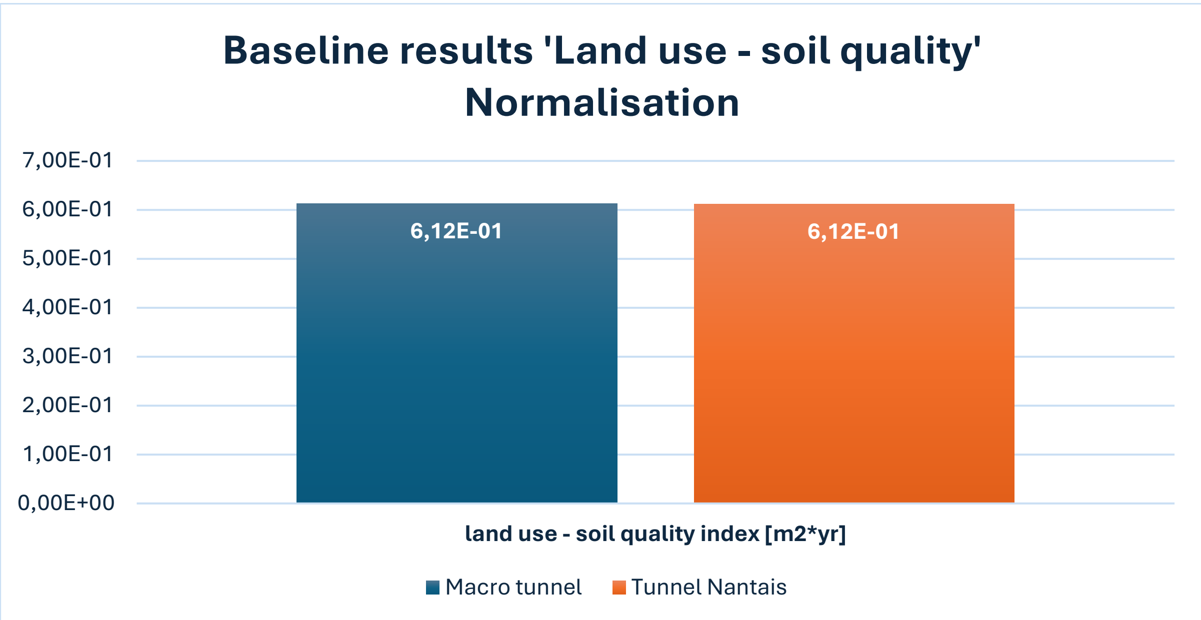

Figure 7. Baseline normalisation results Land use – soil quality

Category	Unit
acidification	mol H+-Eq
climate change	kg CO2-Eq
ecotoxicity: freshwater	CTUe
energy resources: non-renewable	MJ, net calorific value
eutrophication: freshwater	kg P-Eq
eutrophication: marine	kg N-Eq
eutrophication: terrestrial	mol N-Eq
human toxicity: carcinogenic	CTUh
human toxicity: non-carcinogenic	CTUh
ionising radiation	kBq U235-Eq
land use	dimensionless
material resources	kg Sb-Eq
ozone depletion	kg CFC-11-Eq
particulate matter formation	disease incidence
photochemical oxidant formation	kg NMVOC-Eq
water use	m3 world eq. deprived

Figure 8. Impact categories and their units.

5.3. Contribution Analysis

As discussed in the normalisation results, the contribution analysis will study the processes with the greatest relative impact on the following four established categories: land use – soil quality, particulate matter formation, human toxicity (carcinogenic), and material resources.

Figures 9 shows which processes contribute most to human toxicity (carcinogenic) in the Macro tunnel and the tunnel Nantais systems. Both systems show high contributions from waste treatment processes. For the macro system, four processes contribute almost equally: treatment of electric arc furnace slag (24%), polyvinylchloride burning (24%), coking (21%), and polyethylene burning (20%). This reflects a wide variety of heavy industry inputs and emissions to the system.

For Nantais, the most dominant contributor is again the burning of polyvinylchloride (38%), followed by electric arc furnace slag (26%), and coking (23%). Overall, both systems show high impact of fossil-based materials, but the stronger dominance of few contributors in the Nantais system suggests lower material diversity. The category 'others' represents an aggregation of all processes that individually contribute less than the threshold of 2% (Ecoinvent, 2024). These could be aluminium processing, concrete production, municipal solid waste treatment, or rubber production.

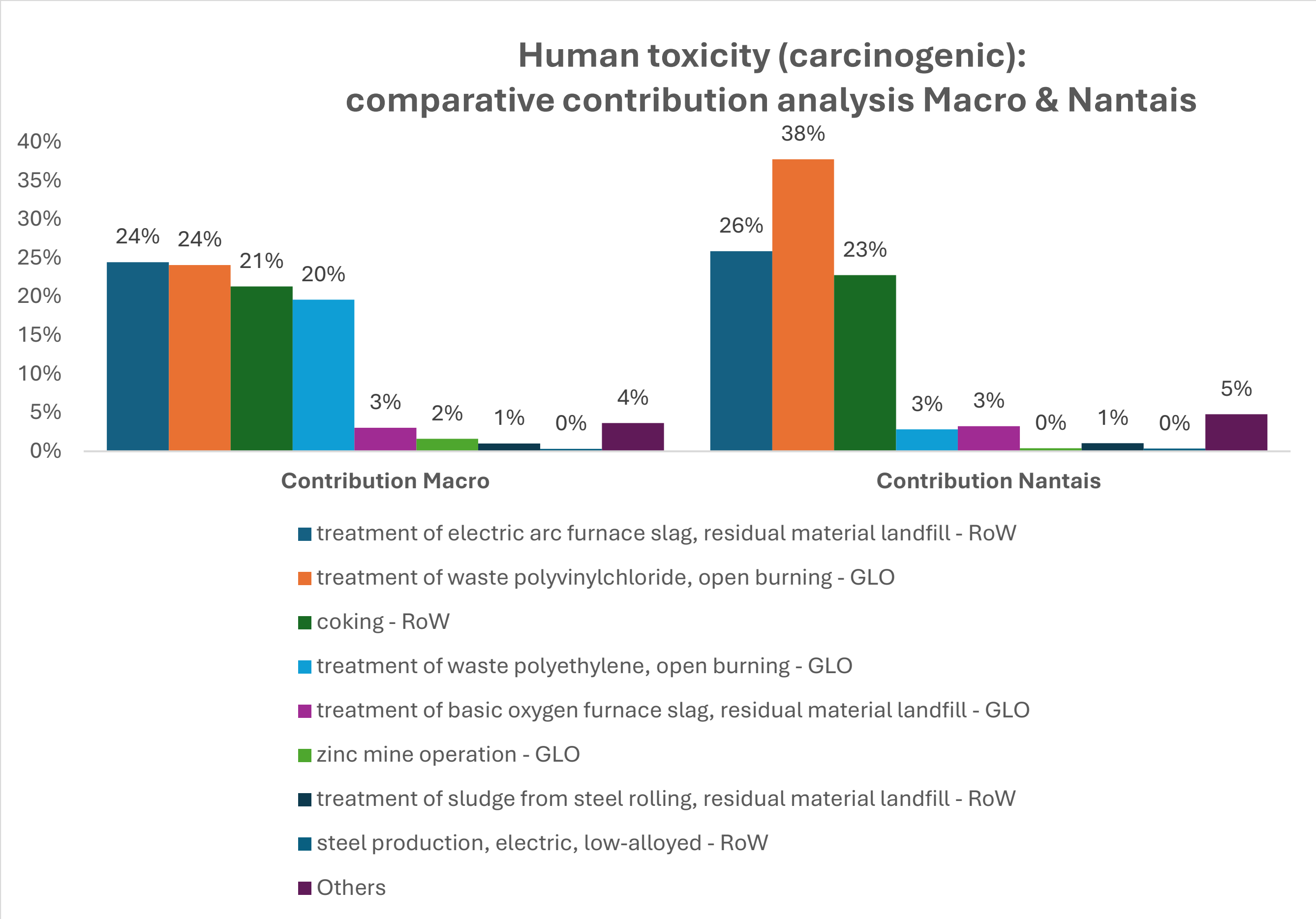

Figure 9. Contribution of individual processes to human toxicity, in Macro and Nantais tunnel systems.

Figure 10 shows the contribution of individual processes to particulate matter formation for both systems. In the Macro tunnel system, the top contributors are dominated by waste management processes. The treatment of waste polyethylene in unsanitary landfills accounts for 39%, followed by open dump disposal (27%) and open burning of polyvinylchloride (11%). These are all related to the disposal of plastic materials used in tunnel construction or maintenance. In comparison, the Nantais tunnel shows a different profile: open burning of polyvinylchloride alone contributes the most with 39%, mainly reflecting the fertiliser use, while landfill and dump treatments account for smaller shares (12% and 8%, respectively).

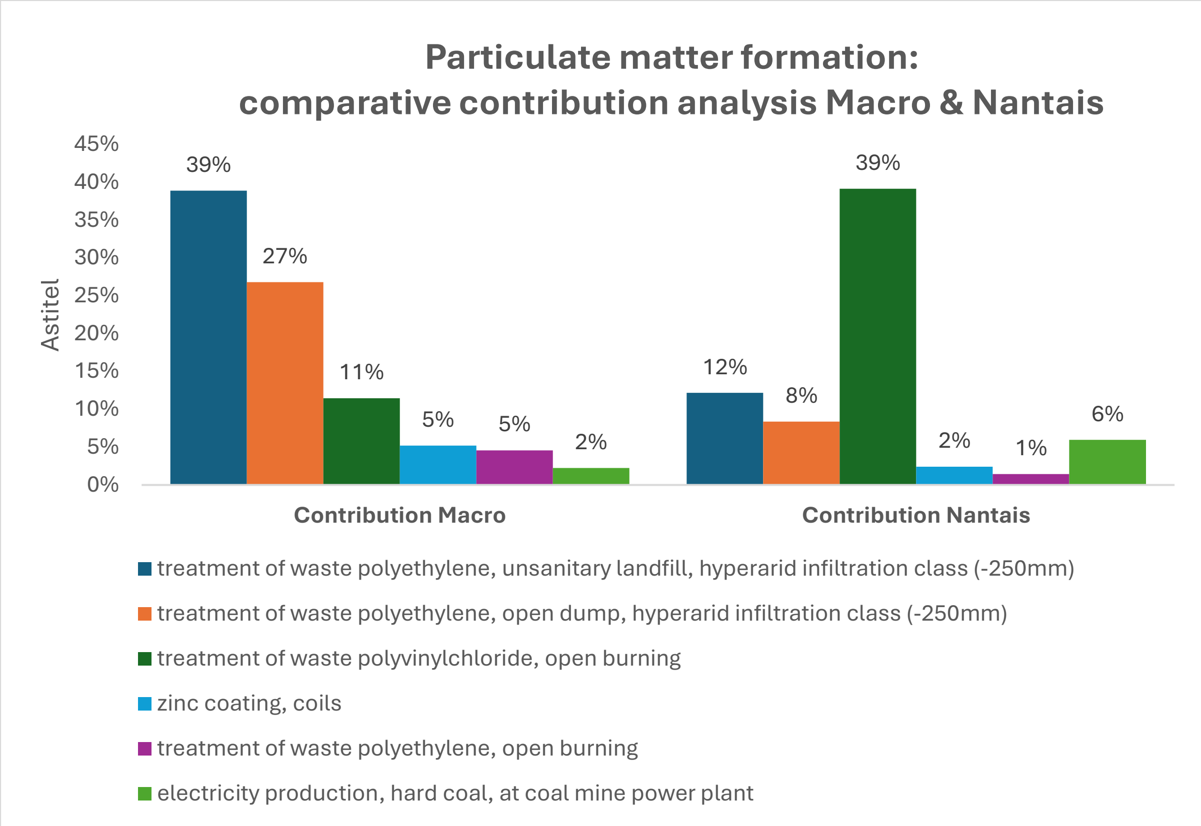

Figure 10. Contribution of individual processes to particulate matter formation, in Macro and Nantais tunnel systems.

The land use impact profile (Figure 11) shows a clear distinction between two main contributors and less present processes. Peat moss production and road construction are the major contributors, at 21% and 20% respectively for Macro and 37% and 25% respectively for Nantais. Peat moss mainly stems from strawberry seedling growing but it can also used as fuel for combustion (Ecoinvent, 2021). Macro contributions are followed by smaller shares from mining, landfill construction, and petroleum infrastructure (each below 5%). This indicates that land occupation is largely driven by raw material extraction and the transport infrastructure required. Although two processes stand out, the Nantais system is more concentrated, making the total impact more dependent on peat has a stronger influence on this category.

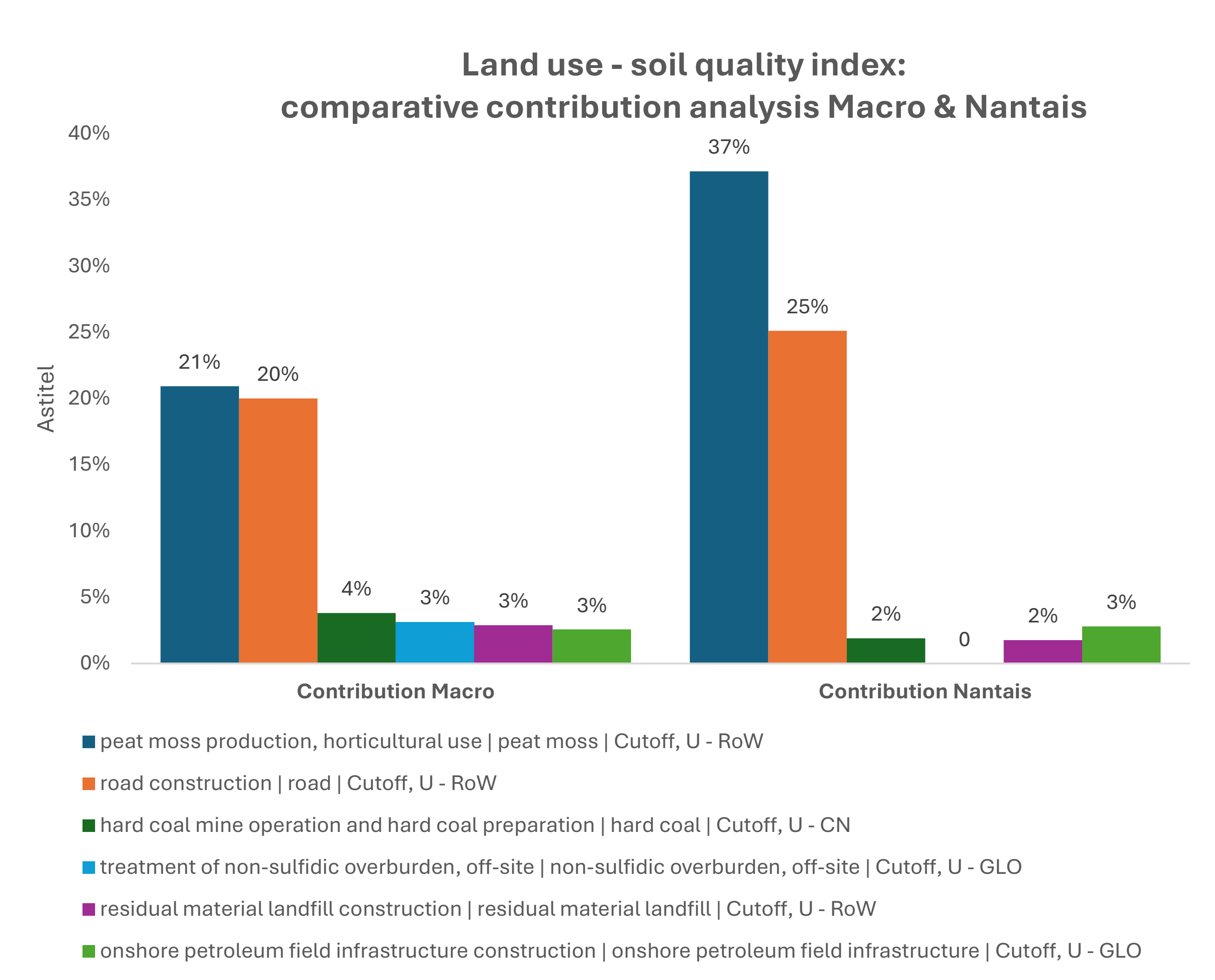

Figure 11. Contribution of individual processes to land use and soil quality, in Macro and Nantais tunnel systems.

The impact of material resource depletion impact (Figure 12) is particularly high in the Macro tunnel system, with zinc mining alone accounting for 68% of the total impact. This is substantially more than any other single contributor in either system. The next contributors (silver and copper mining operations) each account for 4% or less. In contrast, the Nantais tunnel system shows a more balanced distribution: zinc mining contributes 28%, and copper-related processes range from 7% to 8% each. The high contribution from zinc in the Macro tunnel is likely due to the use of galvanized steel for structural components, which is used in larger quantities than in the Nantais system.

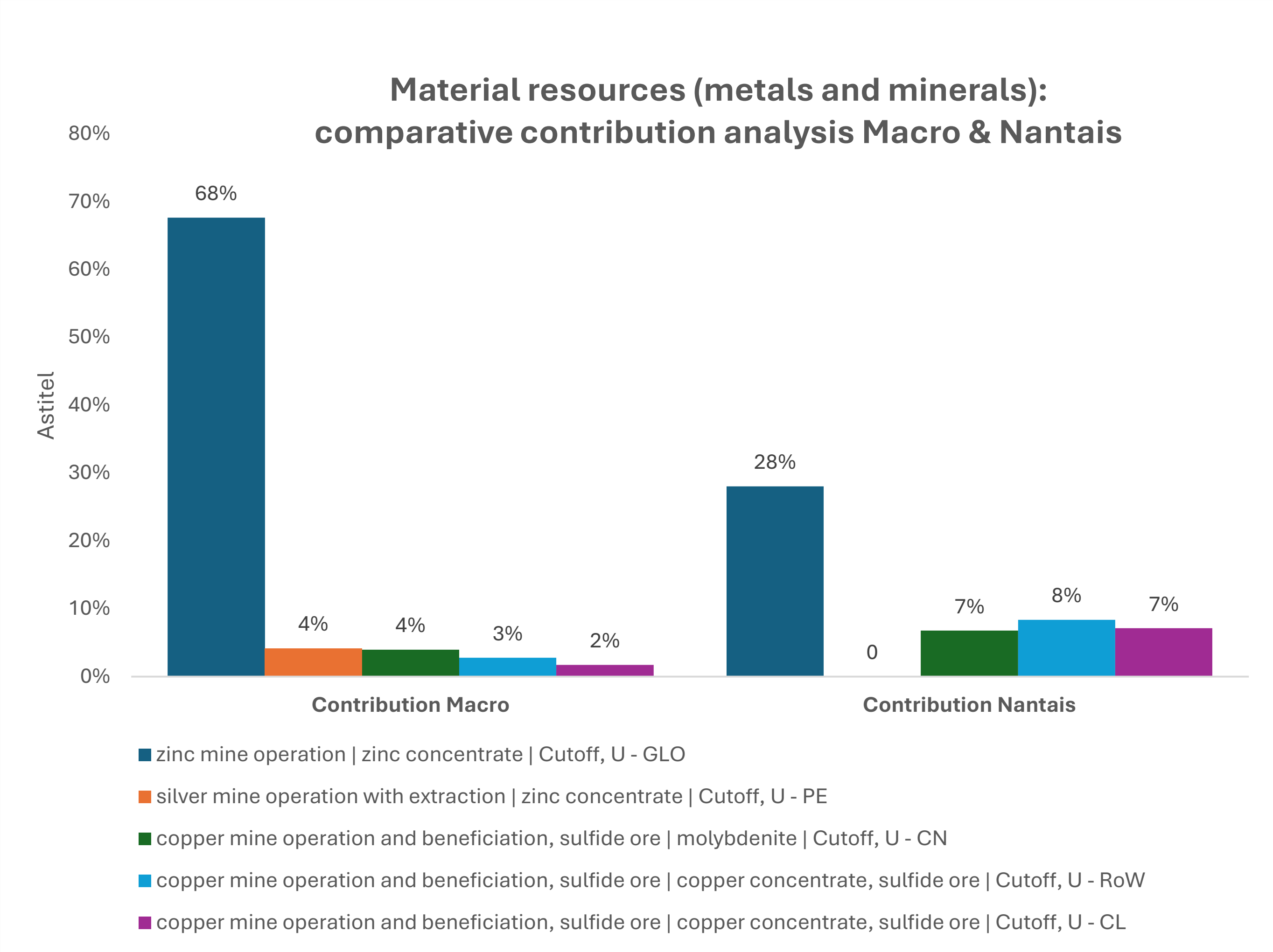

Figure 12. Contribution of individual processes to material resources, in Macro and Nantais tunnel systems.

5.4. Sensitivity Analysis – impact method family

To test the robustness of the LCA results agains the choice of impact assessment method, Table X below compares the characterisation results of EF v3.0 and ReCiPe 2016 v1.03.

Table 4. Characterisation results impact method families: EF v3.0 & ReCiPe 2016 (v1.03).

Impact category	Unit	EF x Macro	EF x Nantais	ReCiPe x Macro	ReCiPe x Nantais
Climate change	kg CO2-Eq	4,36	0,8985	4,3	0,89
Eutrophication (P)	kg P-Eq	0,00081	0,00023	0,00081	0,00023
Eutrophication (N)	kg N-Eq	0,00389	0,00099	0,00091	0,0000697
Ozone depletion	kg CFC-11-Eq	3,63E-08	1,19E-08	0,0000013	0,000000624

The values show a high level of consistency between EF and ReCiPe for climate change and freshwater eutrophication (P), with less than 2% variation across both tunnel systems (Figure 13). This shows that conclusions regarding these two categories are method-independent and robust to the choice of impact method. On the other hand, differences arise in marine eutrophication (N) and ozone depletion potential (ODP): eutrophication shows differences up to 93% and ozone depletion even up to 5144%. This reflects methodological sensitivity for these two categories. Guinée et al. (2002) do not give thresholds or acceptable difference levels between methods, but it states that sensitivity analysis on impact assessment methods has the main purpose of how conclusions may change depending on the impact method chosen. The analysis is not established for validation of the families.

Moreover, as seen in the normalisation results, marine eutrophication and ozone depletion do not contribute significantly to the environmental impact of the systems. Therefore, although method sensitivity is high for these categories, they have a limited influence on the overall interpretation of the LCA.

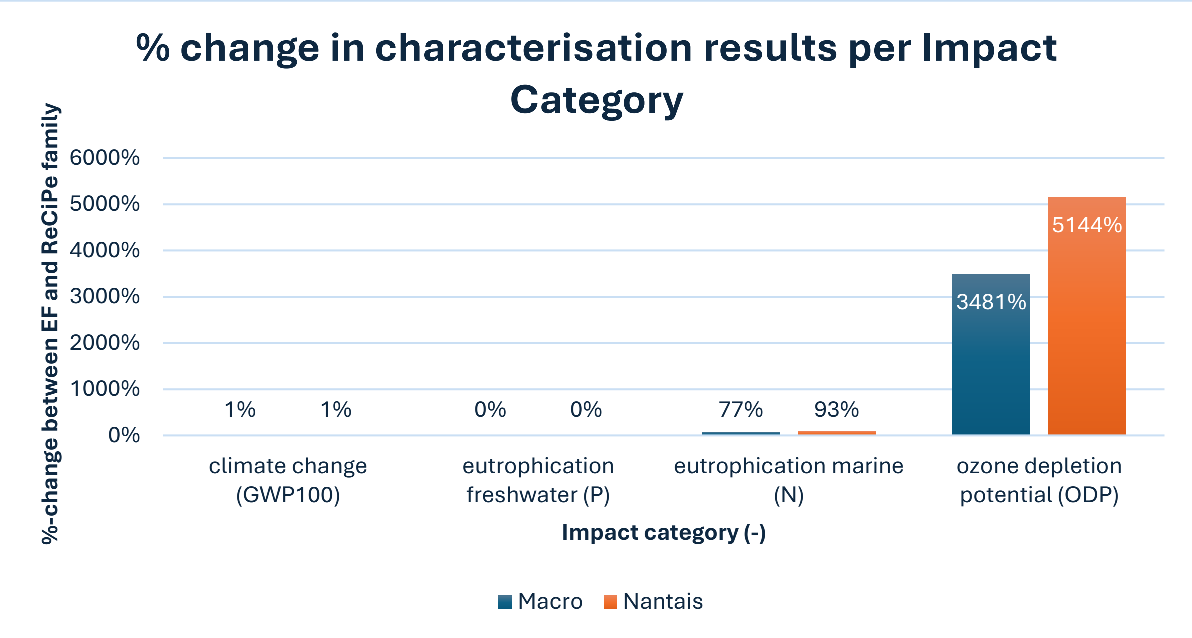

Figure 13. Sensitivity on characterisation results between EF and ReCiPe impact method families.

6. Results – Economic Assessment

This chapter presents the results of the economic assessment of the two systems in the RSK+L region: Macro tunnel strawberry cultivation, and tunnel Nantais strawberry cultivation. The economic assessment consists of the results on the four economic indicators: Net Present Value (NPV), Internal Rate of Return (IRR), Return of Interest (ROI) and Payback Period (PP). Additionally, a sensitivity analysis is executed on four variables and their results on the economic indicators.

6.1. Economic indicator results

Table 5 provides a summary of the key economic results, with values rounded up for clarity and ease of comparison. The full dataset, including unrounded figures and detailed calculations, is available in Appendix E.

Table 5. Baseline results – Economic indicators.

Baseline scenario				
Economic Indicator	**Macro**	**Nantais**	**Ratio Macro vs Nantais**	**Ratio Nantais vs Macro**
Net Present Value (MAD/ha)	907.000	690.000	**1,31**	0,76
Internal Rate of Return (%)	97%	102%	0,95	**1,05**
Return Of Interest (-)	8,75	9,20	0,95	**1,05**
Payback period (years)	1,03	0,98	**1,05**	0,96

Note: Bold for better performing alternative.

a. Net Present Value (NPV)

The Macro tunnel system yields a higher NPV of 907.000 MAD/ha, compared to 690.000 MAD/ha for the tunnel Nantais. This means that, over a 10-year period, Macro generates a 1,3 times higher present value of future profits. While both systems are financially viable, the Macro tunnel offers stronger long-term returns.

b. Internal Rate of Return (IRR)

The IRR represents the annual return generated by the investment. It is 97% for the Macro system and 102% for the Nantais tunnel. Though these values are high compared to traditional sectors, they are considered realistic within the context of strawberry farming, which is characterized by relatively low upfront costs and short revenue cycles (Ihoume et al., 2023).

c. *Return of Interest (ROI)*

In other words, for every 1 MAD invested, the Macro system returns 8.75 MAD, and Nantais 9,20 MAD. Despite Macro's higher absolute profits, Nantais scores slightly better on ROI due to its lower initial investment, resulting in a 1,05 times higher return per unit invested.

d. *Payback period (PP)*

The payback period reflects the time required to earn back the initial investment. Both systems recover their initial investment within approximately one year. The Macro tunnel system reaches its breakeven point after 1,03 years, while tunnel Nantais recovers its costs even faster, after only 0,98 years. In general, these numbers are very low, though strawberry farming is known for low payback periods (Ihoume et al., 2023). These fast payback periods reflect the overall profitability of strawberry farming in the RSK+L region with fast high returns, confirmed by Messem (2025).

6.2. Sensitivity Analysis – economic parameters

To assess the robustness of the economic results, a sensitivity analysis was conducted on four key parameters: percentage of yield sold to fresh market, total yield per hectare, discount rate, and subsidies presence. The analysis evaluates how changes in these parameters affect the main economic performance indicators: NPV, IRR, ROI and PP, and on the water use. The results are presented in Tables 6 and 7, with a full visualisation and calculations included in Appendix E.

Tabel 6. Sensitivity Analysis of Net Present Value and Internal Rate of Return for Macro and Nantais tunnel systems.

Indicators / Variables	NPV macro (MAD/ha)	NPV nantais (MAD/ha)	IRR macro (%)	IRR nantais (%)
Percentage to fresh market (%)				
5	-	4,22E+05	-	68%
10	5,05E+05	-	61%	-
15 (base Macro)	-	6,90E+05	-	102%
25 (base Nantais)	9,07E+05	9,58E+05	97%	135%
40	1,31E+06	-	133%	-
Yield (ton/ha)				
30	3,32E+05	1,82E+05	45%	37%
40 (base)	9,07E+05	6,90E+05	97%	102%

50	1,48E+06	1,20E+06	149%	165%
Discount rate (%)				
3	1,42E+06	1,08E+06	97%	102%
7	1,09E+06	8,30E+05	97%	102%
10 (base)	9,07E+05	6,90E+05	97%	102%
Drip irrigation subsidies (%)				
0 (base)	9,07E+05	6,90E+05	97%	102%
40	9,24E+05	7,07E+05	107%	117%
80	9,40E+05	7,23E+05	119%	137%

Tabel 7. Sensitivity Analysis of Return of Investment, Payback Period, and Water use for Macro and Nantais tunnel systems.

Indicators / Variables	ROI macro (-)	ROI nantais (-)	PP macro (years)	PP nantais (years)	Water use (m3/ha)	Water use (m3/ha)
Percentage to fresh market (%)						
5	-	5,87	-	1,5	-	175
10	5,15	-	1,6	-	175	-
15	-	9,20	-	1,0	-	175
25	8,75	12,54	1,0	0,7	175	
40	12,35	-	0,7	-	175	-
Yield (ton/ha)						
30	3,60	2,89	2,2	2,6	233	233
40 (base)	8,75	9,20	1,0	1,0	175	175
50	13,90	15,52	0,7	0,6	140	140
Discount rate (%)						
3	8,75	9,20	1,0	1,0	175	175
7	8,75	9,20	1,0	1,0	175	175
10 (base)	8,75	9,20	1,0	1,0	175	175
Drip irrigation subsidies (%)						
0 (base)	8,75	9,20	1,0	1,0	175	175
40	9,73	10,69	0,9	0,9	175	175
80	10,93	12,69	0,8	0,7	175	175

The most influencing parameter is **yield** (ton/ha). A higher yield improves all four indicators, and it is the only parameter affecting the water footprint by improving the water use efficiency. As discussed in chapter 4.2, and detailed in Appendix D, yield is a critical factor in strawberry cultivation, as it can fluctuate strongly due to climate change, pests and soil quality. In the base scenario, the PP is approximately 1 year for both the Macro and Nantais system. However, sensitivity analysis shows a wide variability: PP ranges from 0,7 to 2,2 years for Macro, and 0,6 to 2,6 years for Nantais. NPV for Macro ranges from 332.000 MAD/ha to 1,48 million MAD/ha, reflecting a wide range of profitability. IRR for Macro varies from 45% to 149%, while Nantais ranges from 37% to 165%. ROI for Macro ranges from 3,6 to 13,9 and for Nantais from 2,9 to 15,5. The water footprint is the same for both systems, ranging from 233 to 140 m3/ha.

The **Percentage of yield sold to fresh market** is another highly influential parameter. As discussed in detail in Appendix D, different values were used to reflect realistic scenarios for each system: NPV Macro ranges from 505.000 to 1,31million MAD/ha, Nantais ranges from 422.000 to 958.000 MAD/ha. IRR for Macro varies from 61% to 133%, whereas Nantais varies from 68% 135%. ROI Macro ranges from 5,2 to 12,4, Nantais from 5,9-12,5. PP Macro ranges from 1,6 to 0,7 years, while PP Nantais ranges from 1,5 to 0,7 years. This parameter does not influence the water footprint.

Drip irrigation subsidies have a moderate impact, primarily because they affect only a small part of the initial investment, and not the operational costs or the revenue. However, they still lead to changes in profitability: NPV for Macro ranges from 907.000 to 940.000 MAD/ha, while Nantais NPV ranges from 690.000 to 723.000 MAD/ha. IRR Macro ranges from 97% to 119%, while Nantais ranges from 102% to 137%. ROI ranges from 8,8 to 10,9 for Macro and from 9,2 to 12,7 for Nantais. PP Macro results in a range from 1,0 to 0,8 years, while PP Nantais results in 1,0 to 0,7. The water footprint is not influenced by this parameter.

Last, the **discount rate** has a strong effect on NPV, but it does not influence IRR, ROI, PP, or the water footprint, as these indicators are independent of discounting. The NPV increases from 907.000 MAD/ha at 10%, to 1.090.000 MAD/ha at 7%, and to 1.420.000 MAD/ha at 3%. For the Nantais system, the corresponding NPVs are 690,000 MAD/ha (10%), 830,000 MAD/ha (7%), and 1,080,000 MAD/ha (3%). These results show the sensitivity of NPV to discount rate assumptions.

7. Discussion

This chapter discusses the main findings of the environmental and economic assessment of Macro tunnel and tunnel Nantais strawberry cultivation in the RSK+L region. First, the environmental results are interpreted and discussed. Then, the economic performance of both systems is evaluated. Last, the trade-offs between environmental and economic performance are analysed.

7.1. Environmental Assessment

The results show that the Macro tunnel system has higher environmental impacts than the tunnel Nantais system, largely due to the higher material input requirements. The use of structural materials such as zinc, iron, and polyethylene contributes strongly to resource depletion and toxic substances present in the environment. This illustrates that material inputs shape the environmental profile of strawberry production in the RSK+L region. The highest environmental impact – which is identical for both systems – comes from human land use, resulting in loss of biodiversity, loss of life support function, and desiccation (Guinée et al., 2002, p. 74). This means that the impact is not only driven by tunnel design, but also by common agricultural practices like peat moss extraction and road construction, which are the major contributors in this category. It is important to note that peat moss impact depends on the assumed amount required to produce 1 kg of strawberries, based on the Ecoinvent value of 0,045 kg peat per kg of strawberry seedling. Since no precise allocation factor could be determined, this estimate may over- or understate the true impact of peat use in the system.

When considering particulate matter and human toxicity (impact of substance on human health, disease or death to exposure), the impacts differ per tunnel system. Impacts are primarily linked to plastic waste management, including the disposal of polyethylene plastics, reflected by Pergola et al. (2023). In the Nantais system, the main contributors are the use of PVC material used for mulching, also found by Pergola et al (2023). Black mulch is replaced every year and often landfilled (Messem, 2025), but is necessary to keep high yields (Shankar, 2001). While prolonging the lifespan of mulch would be preferable, it is unclear whether this is technically or economically feasible.

Other high impacts come from potassium chloride, used for fertilisers. While Khoshnevisan et al. (2013) also found N-based fertilisers as the main contribution to open field farming, they only did so for the Macro system and not on the Nantais system, like this study. Although, unlike in Pergola et al. (2023), water use does not appear as one of the main contributors to overall environmental impact in this study, the Macro system still consumes up to five times more water over its the cradle-to-gate life cycle. Given that fertiliser and irrigation use is often inefficient and excessive (Messem, 2025), there is clear potential to reduce the associated environmental impact by improving input efficiency.

Moreover, just like Pergola et al. (2023), this study found significant contribution of zinc mining, covering 68% of the total resource depletion impact for Macro tunnels and 26% for in Nantais tunnels, emphasising the environmental consequences of steel-based infrastructure. Future research should explore if reducing steel volume or its coating, or altering the type of used construction materials could lower the environmental impacts of Macro systems without compromising productivity.

7.2. Economic performance

Both tunnel systems show strong economic performance under current conditions in the RSK+L region, with a NPV over ten years of 907.000 MAD/ha for the Macro system and 690.000 MAD/ha for the Nantais system. Nantais scores slightly better in terms of relative returns: 102% IRR and 9,20 ROI compared to 97% and 8,75 for Macro. Payback periods are short for both systems of around one year. This is consistent with the findings of Ihoume et al. (2023), who observed similarly fast returns in strawberry farming due to low upfront costs and short revenue cycles.

However, the financial structures of the two systems differ. The Macro tunnel requires roughly 40% more initial investment and generates about 13% more annual revenue. This difference is largely due to better access to the fresh export market, which is made possible by the earlier harvest period associated with Macro tunnels. On average, Macro farmers sell 25% of their yield to the fresh market, compared to 15% for Nantais. Since fresh strawberries sell at prices up to three times higher than frozen or industrial ones, this market access forms a second highest influencer of economic profitability.

Yet, the higher initial capital requirement of Macro tunnels poses a barrier for farmers with limited financial means. As a result, tunnel choice in the RSK+L region often reflects financial capacity: capital-intensive Macro systems are typically used by export-oriented growers, while the more affordable Nantais tunnels are common among smaller-scale or domestic-oriented producers (Hubert & Kroesen, 2024; Messem, 2025). Farmers with limited financial resources may choose Nantais due to its lower entry costs, or they may have no alternative. Due to the aggregated operational cost data provided by Messem (2025), it is unclear which specific components contribute most to these costs.

This divide shows potential for policy intervention. While Macro tunnels offer higher income potential, their accessibility is often limited. The Moroccan government could consider subsidising part of the initial investment cost to improve access to high-value markets. However, the actual effect on affordability and adoption should be further investigated. The sensitivity analysis indicates that one-time subsidies for drip irrigation have limited impact on economic performance, whereas subsidising the total initial investment may have a stronger effect on improving affordability.

Apart from fresh market access, yield tests strong on the economic performance of both systems, making yield protection essential for the farmers. Higher yields improve all economic indicators. However, this study assumes equal productivity for both systems with 40 tons per hectare, Messem (2025), but similar yields may not reflect reality. Yara (2018) and Haifa-group (n.d.) suggest that Macro tunnels can outperform low tunnels in yield, while Menzel (2025) reports similar yields between the two. Future research should investigate actual yield differences between Macro and Nantais systems in the RSK+L region to validate the equal productivity assumption.

8. Conclusion

This study assessed the environmental and economic performance of two widely used strawberry cultivation systems in Morocco's RSK+L region: Macro tunnels and tunnel Nantais. In a context where strawberry farming is both a key contributor to the regional and national economy, and a driver of land degradation and freshwater use, understanding the trade-offs between environmental impact and profitability is essential. To address this knowledge gap, the study aimed to answer the following research question:

"What are the environmental and economic trade-offs between Macro tunnel and tunnel Nantais systems in strawberry farming in Morocco's RSK+L region?"

The findings show a clear trade-off between economic profitability and environmental sustainability. The Macro tunnel system is more profitable in absolute terms, primarily due to its superior fresh market access enabled by earlier harvest. However, this comes at the cost of higher environmental impacts, largely driven by the use of zinc-coated steel, polyethylene tunnel covers, and emissions linked to steel production. In contrast, the tunnel Nantais system has a lower environmental impact due to lower material and energy input. Although it generates less revenue overall, it remains economically viable due to its low investment requirements.

Both tunnel systems present opportunities for environmental improvement beyond structure design. Inefficiencies in irrigation, fertiliser application, and pesticide use are widely present, can be improved by better farming practices, and would reduce the environmental impact of both systems.

The trade-off between environment and profitability is not only technical but also social. Macro tunnels are often inaccessible to farmers in the region due to their high initial investment costs, although the exact proportion of excluded growers remains unknown. As a result, access to the most profitable production model is not solely a matter of agricultural preference, but one shaped by capital availability and potential structural inequality among farmers in the region.

Improving farming efficiency is a necessary and clear step, yet the environmental and economic trade-offs involved are complex. They are shaped not only by technical factors but also by social dynamics, reflecting the priorities of policymakers and the varying capacities and limitations of farmers and the agricultural sector as a whole.

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10. Appendix

The Appendices of this study can be found in the Excel sheet "Wout_vanKints_IE_final_Appendices".

The Excel contains of the following Appendices:

Appendix	Content
A	Data collection
B	Macro – Unit process data
C	Nantais – Unit process data
D	Assumptions-Modelling choices
E	Water & Economic assessment
F	LCA01 - Inventory results
G	LCA02 – Characterisation
H	LCA03 – Normalised
I	LCA04 – Contribution
J	LCA05 – Family sensitivity