Environmental Challenges 22 (2026) 101396

Contents lists available at ScienceDirect

Environmental Challenges

journal homepage: www.elsevier.com/locate/envc

Ecological hotspots across the global citrus supply chain: A comprehensive life cycle assessment

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ARTICLE INFO

Keywords:
Citrus value chain
Sustainability
Carbon footprint
life cycle impact assessment (LCIA)
Transcontinental cold chain
environmental footprint EF 3.1

ABSTRACT

Global demand for fruits and vegetables is rising, intensifying pressures on land, water, and energy, and driving post-harvest losses that waste ∼30% of annual production. Such losses, together with energy-intensive cold chains, amplify greenhouse gas emissions. Amidst these concerns, the environmental impact of the fruit and vegetable value chain, particularly the transcontinental cold chain, is gaining attention but remains largely unexplored. Here, we quantify the environmental impacts of the intercontinental citrus supply chain from South Africa to the Netherlands using life cycle assessment. By evaluating 16 impact indicators, including water use, land use, freshwater ecotoxicity, and marine eutrophication, we capture hidden burdens typically overlooked in carbon-focused studies. Cultivation dominates water-use impacts (99%), exacerbating risks in water-scarce regions, and accounts for 68% of freshwater ecotoxicity due to chemical inputs. In the post-harvest stages, overseas shipment contributes 62% to the impact of photochemical ozone formation and 52% to the impact of marine eutrophication, highlighting the need for low-carbon transport solutions. Cardboard box production for transport ranks as the second-highest post-harvest contributor to environmental impacts. Aggregated into a weighted single score, pre-harvest activities contribute 56% of total impacts, primarily from irrigation and agrochemicals. These findings pinpoint the ecological hotspots in global fruit trade and underscore the urgency of sustainable irrigation, low-carbon logistics, and material efficiency. Our holistic approach not only identifies ecological hotspots across a real-world, global fruit chain but also establishes citrus as a model system for assessing the sustainability of perishable, globally traded commodities. Our results provide a robust evidence base for policy, supply chain optimisation, and digital tools that support sustainable intercontinental food systems.

1. Introduction

Agro-food chains are complex systems, encompassing activities related to food cultivation, processing, distribution, preparation, and consumption. These systems are responsible for approximately 40 % of global greenhouse gas emissions (UN, 2020). Especially, the global fruits and vegetable value chain significantly contributes to the environmental impact of food, mainly due to the resources and energy required to grow, harvest and transport them (Cassani and Gomez-Zavaglia, 2022; Springmann et al., 2022; Xu and Jain, 2021). Between 2000 and 2020, global fruit production increased by 55 %, while vegetable production saw a 65 % surge during the same period (FAOSTAT, 2022). In 2021, worldwide fruit production reached 910 million tons, and vegetable production reached 1.2 billion tons. This massive yearly production demands substantial resources such as land, water, and energy, often from fossil fuels, thus significantly contributing to the environmental burden of the food industry across many countries in the world. The continuous use of synthetic fertilizers and pesticides in fruit and vegetable production also contributes to greenhouse gas emissions. Furthermore, about one-third of the world's fruits and vegetables are lost or wasted annually along the entire food value chain (Bellù, 2017; Bancal and Ray, 2022). This high level of food loss represents a significant loss of water and energy, thereby contributing to global greenhouse gas emissions (Cassou et al., 2020; Garnett, 2006; Lake et al., 2015). These emissions reached a staggering ∼40 gigatonnes of CO_2 equivalent in 2021 (IEA, 2022).

In response to escalating concerns over the environmental impacts of

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https://doi.org/10.1016/j.envc.2025.101396
Received 27 September 2025; Received in revised form 18 November 2025; Accepted 16 December 2025
Available online 17 December 2025

Nomenclature

AC	acidification (impact category)
CC	climate change (impact category)
CO	Carbon oxide
Ecotox	ecotoxicity freshwater (impact category)
EF	Environmental Footprint
EU_f	eutrophication freshwater (impact category)
EU_m	eutrophication marine (impact category)
EU_t	eutrophication terrestrial (impact category)
HTox_c	human toxicity, cancer effects (impact category)
HTox_nc	human toxicity, non-cancer effects (impact category)
IR	ionising radiation (impact category)
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	land use (impact category)
OD	ozone depletion (impact category)
POF	photochemical ozone formation (impact category)
RU_f	resource use-fossil (impact category)
RU_mm	resource use-mineral and metals (impact category)
SDG	Sustainable Development Goal
WU	water use (impact category)

food production and consumption, policy interventions have intensified. The European Union (EU) has adopted targeted strategies to reduce the environmental footprint of its food system. One notable initiative is the "farm to fork strategy" (CEC, 2020), designed to specifically reduce the environmental footprint of the food system, with a particular emphasis on fruits and vegetables. Despite these alarming trends, the comprehensive environmental impacts of the global fruit and vegetable value chain, particularly for high-volume crops like citrus, remain underexplored. Quantifying these impacts is essential to achieving sustainable food systems, reducing food loss, and advancing the *United Nations Sustainable Development Goals under SDG 12, "responsible production and consumption"*.

Citrus is among the most varied and widespread fruit crops in both the North and South hemispheres, cultivated in over 140 countries on small, medium and large farms and exported to more than 60 countries as fresh produce or processed product (FAO, 2021). Citrus is consumed at very large scales. The EU alone imports approximately 1.22 million tons of citrus annually, mainly from countries like Egypt, Morocco, South Africa and Brazil (ProducePay, 2023). At such volumes, even relatively small environmental burdens per kilogram translate into substantial cumulative impacts, making the 1-kg functional unit highly relevant for sustainability assessments. For instance, a conservative estimate of ~0.6 kg CO_2-eq per kg of fruit (Wu et al., 2019) implies total emissions of over 700,000 tons of CO_2-eq per year from citrus consumption in the EU alone. Citrus cultivation typically makes use of pesticides and fertilizers, which in the long run, can lead to soil contamination and the accumulation of toxic elements, posing a severe threat to the environment (Burchardt et al., 2021; Triantafyllidis et al., 2020). Citrus orchards often operate as highly intensive systems, requiring considerable amounts of irrigation water, especially in the current climate change conditions (Bazrafshan et al., 2019; Vincent et al., 2020). After citrus are harvested, they undergo processes of cleaning, packaging, transportation, consumption, and waste disposal, which require long transport distances, also in intercontinental value chains and are energy-demanding (Wu et al., 2019; Onwude et al., 2022). All these steps contribute to greenhouse gas emissions, with citrus fruits alone accounting for over ~15 % of global fresh food production (FAO, 2022). Because citrus relies on refrigerated intercontinental supply chains and water- and energy-intensive production, understanding the environmental profile of 1 kg of citrus provides meaningful insight into the broader climate, water, and resource implications of a major global fruit commodity. One way to understand and quantify the environmental impact of all these processes in the citrus value chain is to conduct a life cycle assessment (LCA) study, which over the past few years has marked a big step into the scientific literature (e.g. Notanicola et al., 2015; Dijkman et al., 2018; Cucurachi et al., 2019). Conducting a life cycle assessment (LCA) of the intercontinental citrus value chain provides critical value by comprehensively capturing both pre- and post-consumption emissions, as well as embodied emissions across the entire citrus value chain, enabling a holistic understanding of environmental impacts from production to disposal.

Life Cycle Assessment (LCA) studies have extensively evaluated the environmental impacts of citrus cultivation across diverse regions, including Italy (Falcone et al., 2020), Spain (Martin-Gorriz et al., 2020), Nigeria (Ogunlade et al., 2020), Mexico (Bonales-Revuelta et al., 2022). These studies primarily focus on pre-harvest stages, employing cradle-to-farm-gate LCAs to assess impacts like greenhouse gas (GHG) emissions, energy use, and water consumption, often using region-specific datasets. For instance, Falcone et al. (2020) emphasized energy-intensive irrigation in Italy, while Ogunlade et al. (2020) highlighted land use impacts in Nigeria. However, their scope rarely extends beyond farm boundaries, and impact categories vary, with limited inclusion of ecotoxicity or land degradation. In contrast, post-harvest processes, such as processing, packaging, transcontinental transport, and end-of-life disposal, remain underexplored, particularly for their contributions to water use, land use, and non-GHG impacts. Existing studies assess regional pre-harvest citrus farming, but no work has linked African production with European consumption in a full transcontinental chain. Wu et al. (2019) calculates the carbon footprint of the citrus post-harvest cold chains, focusing exclusively on GHG emissions using a simplified process-based LCA model. Their study omitted critical dimensions like freshwater ecotoxicity, eutrophication, and resource depletion, and lacked granular process-level analysis of post-harvest stages and did not povide a multi-indicator, cradle-to-grave assessment. Similarly, existing literature (Pernollet et al., 2017; Beccali et al., 2009; Cabot et al., 2022; du Plessis et al., 2022; Cerutti et al., 2014) seldom disaggregates the individual contributions of post-harvest processes or integrates pre- and post-harvest impacts holistically, limiting insights into ecological hotspots across the global fruit and vegetable value chain. This lack of system-wide, multi-indicator analysis leaves policymakers, retailers, and consumers without clear evidence on the hidden ecological burdens of imported fruit, such as ecotoxicity or marine eutrophication, which are highly relevant for current EU Farm-to-Fork and climate policies.

In the EU, where citrus consumption is high and sustainability goals are ambitious, the comprehensive analysis of the environmental impacts associated with the value chain of citrus could provide valuable scientific evidence to guide policy, trade, and consumer choices, helping to align food consumption with broader environmental and climate objectives.

Therefore, to address the existing gaps, we conduct a comprehensive LCA of the transcontinental citrus supply chain, building on methodological recommendations from Cabot et al. (2022) for robust inventory modelling and impact assessment. To our knowledge, this is the first study to integrate both South African pre-harvest production and the complete post-harvest chain to the Netherlands within a single LCA framework, thereby bridging the common farm-gate–to–market disconnect found in earlier studies. Unlike Wu et al. (2019), which used a narrow carbon-focused approach, our study: (i) extends the life cycle inventory (LCI) to model both pre-harvest activities in South Africa and the full post-harvest supply chain to the Netherlands, capturing processes like packaging, refrigerated transport, and waste management; and (ii) evaluates 16 environmental indicators, including GHG emissions, water use, land use, freshwater ecotoxicity, and marine eutrophication, to identify ecological hotspots. By disaggregating individual process contributions and going beyond carbon footprints to include underrepresented categories such as ecotoxicity and eutrophication, we reveal hidden burdens of citrus trade that are directly relevant for EU Farm-to-Fork and climate policies. Moreover, citrus is used here as a model system for globally traded, perishable fruit commodities, meaning our findings can inform sustainable sourcing strategies and consumer choices beyond citrus alone. By integrating pre- and post-harvest stages and disaggregating process-level contributions, we provide a holistic assessment of citrus as an exemplary fruit. This offers both methodological advancement for LCA research and actionable insights for policymakers, retailers, and consumers in the shift toward environmentally sustainable food production and consumption systems.

South Africa is the world’s second-largest citrus exporter, trailing only behind Spain, contributing to 10 % of global citrus exports (Chisoro and Roberts, 2023; OEC World, 2022). Approximately two-thirds of the country’s citrus production is exported as fresh fruit, mostly to the EU (about 41 %), of which 48 % goes to the Netherlands (Tralac, 2023). LCA is used herein as the methodology of reference as it is an established comprehensive framework that serves multiple purposes, including providing empirical data for decision making. Indeed, LCA offers scientific foundations for product design policies, tracking progress within the sector towards achieving sustainable development goals (Gava et al., 2020; Sala et al., 2021), and aids in informing consumers about the environmental impacts within the food value chain.

2. materials and methods

LCA is chosen as a representative methodology to perform the assessment of the potential environmental sustainability of an exemplificative international citrus value chain. LCA is performed according to the ISO 14040 and 14044 standards (ISO, 2006a, 2006b), following the following four iterative steps:

- definition of the goal and scope of the system under study;
- compilation of the life cycle inventory (LCI), meaning the inventory data of relevant inputs (e.g., natural resources, energy) and output (e.g., emissions to air, water and soil) from and to nature, generated by the system under study;
- quantitative assessment of the potential environmental impacts associated with these inputs and outputs;
- interpretation of the results of inventory analysis and impact assessment in accordance with the goal of the study.

2.1. Goal and scope

The goal of this LCA study is to improve the LCI of the intercontinental citrus value chain from farm in South Africa to fork in the Netherlands presented in Wu et al. (2019) with more recent and primary data and identify the hotspots of impacts for various environmental indicators beside the typically analysis of global warming potential, thus including eutrophication, water scarcity, land use impacts, and aquatic ecotoxicity among others. Particularly, we aim to highlight the stages of the supply chain and the processes which mostly generate environmental burden and the main reasons behind, considering the limitations associated with the information collected and the modelling choices.

The consumption of 1 kg of orange in 2023 in The Netherland is used as the functional unit. Orange was chosen as representative fruit among the citrus species because they represent the most cultivated types, accounting for more than half of global citrus production, they are widely exported from South Africa to EU, especially to the Netherlands (FAO, 2023), and previous studies provide relevant information that are used in this analysis (Wu et al., 2018; 2019). The exemplificative structure of the supply chain is shown in Fig. 1.

The system boundaries can be considered "from farm to fork" since the examined system includes all the stages from the cultivation of citrus to their consumption, passing through harvest, packaging, pre-cooling, overseas transport, storage, regional transport, and retail.

The production processes from cultivation to pre-cooling are assumed to be located geographically in South Africa. The steps from the Storage Centre onward are all located in the Netherlands, where we assumed that the oranges are locally consumed.

2.2. Life cycle inventory analysis

We constructed the LCI representing an average international citrus value chain, capturing the key stages and processes involved in citrus production, distribution and consumption, using the work of Wu et al. (2019) as a starting point. Extensive data were collected to ensure a robust foundation for the analysis. Specifically, information about the citrus value chain were collected from research groups investigating the international citrus value chain and local citrus export companies in South Africa and completed with data from literature. Sources of data from literature include scientific articles, technical reports, online databases (e.g. FAOSTAT) and additional grey literature as websites of companies.

For the background data, version 3.9.1 of the database ecoinvent (ecoinvent 2023) in its “Allocation, cut off by classification” system model was used, as available in Activity Browser v.2.9.7 software (Steubing et al., 2020).

Further details are reported in the next sub-sections. Additionally, detailed LCI for each stage of the value chain, calculations, including formulas and parameters, are reported in the supplementary material (SM) excel file.

2.2.1. Stage 1: cultivation

The cultivation stage was taken directly from ecoinvent v.3.9.1 database. Indeed, ecoinvent has a dataset called "orange production, fresh grade, ZA, 2015″ dedicated to the production of fresh oranges in South Africa, based on data retrieved in 2015 from Confronting Climate Change (CCC, 2015) and national production statistics on average yields.

The dataset describes the cultivation step of oranges to produce 1 kg of fresh oranges aimed to export. The activity includes the nursery producing fruit tree seedlings, the clearing of the orchard and the related waste treatment, soil cultivation, planting trees, irrigation, use of machinery (e.g., tractors for mowing), application of plant protection products and fertilizers, as well as direct field emissions and land use change. Heavy metal uptake by the crop is considered.

2.2.2. Stage 2: packaging and palletization

The packaging and palletization stage occurs in a packhouse in South Africa, in an unspecified location. For the sake of our calculations, the packhouse is assumed to produce 7500 ton citrus per year over a surface of 7500 m^2 (Soleil Sitrus, 2024), and it is located between 0 - 20 km from the fields where the citrus is cultivated based on the communication from South African experts in the citrus industry.

We assumed that citrus fruits are brought with a lorry to the packhouse. Within the packhouse, a thorough sorting process is carried out to eliminate fruits of lower quality that are unsuitable for export. Additionally, any green parts, such as leaves, are removed and repurposed for composting. The remaining fruits undergo a series of steps including washing, waxing, stacking in boxes and eventually arranged in pallets. The Supervent boxes as described in Wu et al. (2019) are used as reference herein, which according to South African experts might lead to a higher impact score compared to other configurations.

For the purpose of environmental impacts assessment, the

Fig. 1. Exemplification of the intercontinental citrus value chain from South Africa to the Netherlands. Some icons used herein have been sourced from flaticon.com.

environmental burden is assumed to be 88 % allocated to the packaging of fresh citrus for export, including associated waste to compost. This value refers to the application of a mass allocation approach, and is the result of a calculation based on available data which considers that around 12 % of citrus which reach the packaging factory is used for other purposes, either sold on the local market or sent to specialized factories for further processing into juice. Different assumptions, e.g. considering a different mass allocation value or applying the economic allocation approach between the main product (i.e. fresh oranges) and by-product (i.e. lower quality fruit) could be considered in the future for further analysis. The final LCI of this step is reported in the SM per 1 kg of packed citrus.

2.2.3. *Stage 3: pre-cooling*

The pre-cooling stage is assumed to occur inside the packhouse or in the immediate proximity of it. Therefore, no transport is accounted for in the LCI. During pre-cooling, fruits are cooled from ambient temperature to a lower temperature. We assumed the following temperature ranges: 12 - 22 °C in September and October in the Eastern Cape (Weather and Climate, 2024a) to 4 °C, based on communication with experts in the citrus industry. The pre-cooler structure is modeled based on the information in Wu et al. (2018) and those received from co-authors after a visit to a facility in South Africa in September 2022. The calculation of energy consumption is based on the procedure presented in Wu et al. (2019). Therefore, no food waste is accounted for in this step of the value chain. The final LCI of this step is reported in the SM per 1 kg of pre-cooled packed citrus.

2.4.4. *Stage 4: overseas transport*

This stage of the citrus value chain implies the road transport of citrus from the pre-cooling site to the port via a refrigerated truck, and the overseas transport from South Africa to the Netherlands via a ship with refrigerated containers. The shipping is assumed to start at Port Elizabeth harbor and conclude at Rotterdam port. The distance between the pre-cooling site and the port in South Africa is assumed to be 149 km (based on personal communication of experts in the citrus industry). The shipping is assumed to span a distance of 12,160 km far and over a period of 26 days (Searoute, 2024). Throughout the overseas transit, electricity for container cooling and its consumption is calculated following the procedure outlined in Wu et al. (2019). Additionally, energy consumption for maintaining the required temperature during the journey is considered. No provisions for food waste are made in this particular phase of the supply chain. The final LCI of this step is reported in the SM per 1 kg of cooled packed citrus.

2.2.5. *Stage 5: storage*

Once the oranges reach the port in Rotterdam, they are stored over 10 days at 0 °C. The external ambient temperature is assumed to be 10 °C, based on average temperature in November in the Netherlands (Weather and Climate, 2024b). The storage center is assumed to be located at the port (CTP, 2022). Therefore, no additional transport by road is included in the LCI. The energy consumed to keep a stable temperature at the storage center is calculated based on Wu et al. (2019). The final LCI of this step is reported in the SM per 1 kg of stored packed citrus.

2.2.6. *Stage 6: retail*

The retail outlet is assumed to be situated in Amsterdam, approximately 73 km away from the Rotterdam port (Bursa Transport, 2022). These retail shops in the Netherlands vary in size, ranging from 800 to 1824,900 m^2 (Zhang et al., 2023). The calculations of the electricity consumption necessary to maintain the optimal temperature inside the retail store and prevent food damage are based on the information provided in Stoessel et al. (2012), considering a storage temperature of 9 °C.

Waste management is addressed at this stage of the value chain. Specifically, cardboard waste is generated from the Supervent cardboard boxes used for transporting the fruit to the retail outlet. Additionally, food waste is accounted for as bio waste, encompassing damaged, expired, unsold, or food rejected after quality controls (EC 2021). Food waste calculations are based on literature, utilizing proxy values for oranges in other European countries such as the UK and Sweden (da

Costa Souza et al., 2021). Specifically, we assumed that 4 % of the stored packed citrus is lost during this phase. The final LCI of this step is detailed in the SM per 1 kg of sold citrus.

2.7.7. Stage 7: consumption

Consumption is assumed to take place within a household located in Amsterdam, 4 km away from the retail store. This represents an average value for Europe (Castellani et al., 2017). Assuming that the oranges are sold as single items, there is no residual packaging left at the retailer for disposal or recycling. The assumed scenario involves the consumer driving 4 km from home to the retail center, purchasing food products including oranges, and then driving 4 km back home, covering a total distance of 8 km. Oranges represent 3 % of the whole basket of food products (proxy from the average European consumption of food products in Castellani et al. (2017)).

Regarding food waste, we assumed that 12 % of the fruit is wasted within households in the Netherlands, in line with the findings of de Cassia Vieira Cardoso et al. (2021). Among these losses, 54 % goes into bio waste, while the remainder is assumed to go to landfill (Van Dooren et al., 2019). The final LCI of this step is reported in the SM per 1 kg of consumed citrus.

2.3. Life cycle impact assessment (LCIA)

The Environmental Footprint v.3.1 (EF 3.1) methodology, developed by the European Commission's Joint Research Centre (EC-JRC) (Zampori and Pant, 2019; EC-JRC, 2022) was used as the LCIA method of choice. The reason for this choice is twofold. The EF is a harmonized and regulatory method, recommended for its use in the EU context (EC, 2013) since it ensures consistency with EU regulations and reporting frameworks, and it allows to calculate the environmental impacts up to the weighted score, using European average conditions representative of the this study's end point (consumption) and facilitating the communication of LCA results especially for decision-making.

This method allows to quantify the potential environmental impacts at midpoint level for the following 16 impact categories: climate change, ozone depletion, ionizing radiation, photochemical ozone formation, particulate matter, human toxicity non-cancer effects, human toxicity cancer effects, acidification, eutrophication freshwater, eutrophication marine, eutrophication terrestrial, ecotoxicity freshwater, land use, water use, resource use- fossils, and resource use- minerals and metals. Furthermore, this method allows to calculate the single score weighted impact by means of normalization and weighting factors (Crenna et al., 2019; Sala et al., 2018), to disclose the environmental impact categories most affected by the overall value chain. The set of weighting factors recommended for EF 3.1 includes weighing factors developed by the EC-JRC through survey to public, experts in LCA and in impact assessment, also including robustness factors. The EF 3.1 method with exclusion of long-term emissions as implemented in the software Activity Browser (v.2.9.7) was used.

3. Results

The possible hotspots of environmental impact were identified by analyzing the environmental impacts of each stage along the whole value chain of citrus. This means the key areas along the citrus value chain where environmental impacts are significant and where actionable interventions are required. On these, the various actors of the citrus value chain could focus to mitigate such impacts. In Table 1, the environmental impacts of each stage of the citrus value chain are reported at

Table 1
Environmental impact of the citrus supply chain unfolded for each stage, expressed according to the unit of each impact category per1 kg consumed citrus. The main contributor for each impact category is highlighted in red, followed by the second highlighted in orange and the third in yellow. AC = acidification terrestrial; CC = climate change; Ecotox = ecotoxicity, freshwater; PM = particulate matter; EU_*m* = eutrophication, marine; EU_*f* = eutrophication, freshwater; EU_*t* = eutrophication, terrestrial; Htox_*c* = human toxicity, cancer effects; Htox_nc = human toxicity, non-cancer effects; IR = ionising radiation; LU = land use; OD = ozone depletion; POF = photochemical ozone formation; RU_*f* = resource use, fossils; RU_mm = resource use, minerals and metals; WU = water use.

Impact category	Unit	1 Cultivation (ZA)	2 Packing house (ZA)	3 Pre-cooling (ZA)	4 Overseas transport (ZA)	5 Store (NL)	6 Retail (NL)	7 Consumer (NL)
AC	mol H+ eq	1.76×10^{-3}	1.99×10^{-3}	7.38×10^{-4}	5.48×10^{-3}	8.83×10^{-5}	1.69×10^{-5}	3.87×10^{-4}
CC	kg CO2 eq	1.09×10^{-1}	2.27×10^{-1}	5.56×10^{-2}	2.39×10^{-1}	1.41×10^{-2}	1.22×10^{-2}	1.34×10^{-1}
Ecotox	CTUe	8.71	1.17	1.18×10^{-1}	1.54	7.76×10^{-2}	2.21×10^{-2}	1.16
PM	disease inc.	1.03×10^{-8}	1.51×10^{-8}	1.86×10^{-9}	8.47×10^{-9}	1.12×10^{-9}	8.71×10^{-10}	5.23×10^{-9}
EU_m	kg N eq	6.15×10^{-4}	4.61×10^{-4}	9.33×10^{-5}	1.52×10^{-3}	1.39×10^{-5}	1.08×10^{-5}	1.05×10^{-4}
EU_f	kg P eq	2.12×10^{-5}	1.79×10^{-5}	4.43×10^{-6}	1.21×10^{-6}	4.75×10^{-7}	-3.29×10^{-7}	1.68×10^{-6}
EU_t	mol N eq	4.97×10^{-3}	3.78×10^{-3}	1.20×10^{-3}	1.68×10^{-2}	3.05×10^{-4}	5.87×10^{-5}	1.18×10^{-3}
Htox_c	CTUh	1.34×10^{-10}	2.29×10^{-10}	3.55×10^{-11}	1.23×10^{-10}	1.76×10^{-11}	1.09×10^{-11}	9.05×10^{-11}
Htox_nc	CTUh	6.47×10^{-9}	4.86×10^{-9}	1.27×10^{-9}	1.13×10^{-9}	1.91×10^{-10}	3.43×10^{-10}	1.39×10^{-9}
IR	kBq U-235 eq	1.48×10^{-3}	4.10×10^{-3}	7.03×10^{-4}	7.07×10^{-4}	3.08×10^{-4}	1.36×10^{-4}	7.48×10^{-4}
LU	Pt	1.75×10^{1}	1.20×10^{1}	2.55×10^{-1}	4.96×10^{-1}	1.68×10^{-1}	1.27×10^{-1}	4.49×10^{-1}
OD	kg CFC11 eq	4.62×10^{-9}	3.40×10^{-9}	1.91×10^{-10}	3.70×10^{-9}	3.03×10^{-10}	3.51×10^{-10}	2.03×10^{-9}
POF	kg NMVOC eq	6.17×10^{-4}	1.11×10^{-3}	2.86×10^{-4}	4.59×10^{-3}	4.83×10^{-5}	6.63×10^{-5}	4.11×10^{-4}
RU_f	MJ	1.65	2.89	7.21×10^{-1}	3.02	1.74×10^{-1}	1.67×10^{-1}	1.20
RU_mm	kg Sb eq	1.82×10^{-6}	7.85×10^{-7}	3.08×10^{-7}	4.31×10^{-7}	1.98×10^{-7}	4.91×10^{-8}	8.68×10^{-7}
WU	m3 depriv.	9.30	7.22×10^{-2}	8.57×10^{-3}	1.05×10^{-2}	3.23×10^{-3}	3.00×10^{-3}	1.53×10^{-2}

midpoint level for the 16 impact categories of the EF 3.1 method. Red values indicate the main contributor for each impact category, followed by the second highlighted in orange and the third in yellow. It is to be noted that, for each impact category, the sum of the impact scores from stage 1 to 7 give the overall environmental impact of the citrus value chain for the specific impact category. Stages 1 (pre-harvest), 2 and 4 (both post-harvest) are the main contributors to the impacts for the overwhelming majority of the impact categories, covering at least 68 % of the total impact per impact category.

An overview of how each stage of the value chain relatively contributes to the impact for each of the 16 impact categories is shown in Fig. 2. The cultivation stage alone is the main contributor to the environmental impact for seven impact categories: water use (99 % of the total impact for this category), freshwater ecotoxicity (68 %), land use (57 %), followed by freshwater eutrophication (circa 45 %), human toxicity non cancer effects and resource use, minerals and metals (both standing at 41 %) and ozone depletion (32 %). This first stage of the citrus value chain is the second contributor to other five impact categories. The activities at the packinghouse represent the main contributors to the environmental impacts for three impact categories, in a range between 35 % (particulate matter) to 50 % (ionizing radiation). This stage has the second highest impact in more impact categories, specifically eight. Overseas transport shows the highest impact for six impact categories, spanning from 30 % in climate change and resource use fossils to around 59 % in terrestrial eutrophication. This stage is the second contributor to the impact associated with freshwater ecotoxicity, covering circa 12 % of the overall value chain impact.

A deeper level of detail is given by analyzing the contribution of the processes constituting each stage of the citrus value chain. Regarding the cultivation stage, irrigation, together with the production and application of fertilizers and crop protection products, are the main environmental burdens for the cultivation stage (see SI for details). Particularly, the impacts to water use are associated with the water consumption for irrigation; the impacts on freshwater ecotoxicity are linked to the production and use of fertilizers, and the emissions of metals and other compounds from the application of chemical substances, while the impacts to land use are associated with the transformation and occupation of land for cultivation purpose. These findings are in line with studies in literature analyzing the production of citrus, mostly oranges, in other regions (e.g., Martin-Gorriz et al., 2020 in Spain)

Regarding the post-harvest stages, overseas shipment, including energy consumption for cooling and keeping a stable, cool temperature (according to the procedure in Wu et al., 2019), carries the highest environmental impacts for six impact categories, ranging from circa 27 % for climate change and resource use- fossil, to circa 62 % in photochemical ozone formation. This goes together with paperboard production for Supervent boxes, used to pack and prepare citrus fruits for shipment; this process shows higher environmental impacts for three impact categories; followed by the electricity consumption at the packaging and palletization step which is the process with the third highest environmental impacts in the post-harvest value chain (see SI for further details).

The study of Wu et al. (2019), whose methodology for calculating the energy consumption along the supply chain was taken as starting point for building the LCI behind the study herein reported, analyses the impacts of the orange supply chain from cultivation to retail in Switzerland. The study does not consider the final consumption step. It was not possible to directly compare the environmental impacts of the present study and of Wu et al. (2019) because of several factors. Specifically, (i) the different impact assessment methods used (i.e. EF v.3.1 vs ReCiPe); (ii) the different system boundaries (from farm to fork vs from farm to retail); and (iii) the geographical location (i.e. the supply chain ends in the Netherlands vs in Switzerland respectively). However, the authors show that overseas transport via ship, including both the

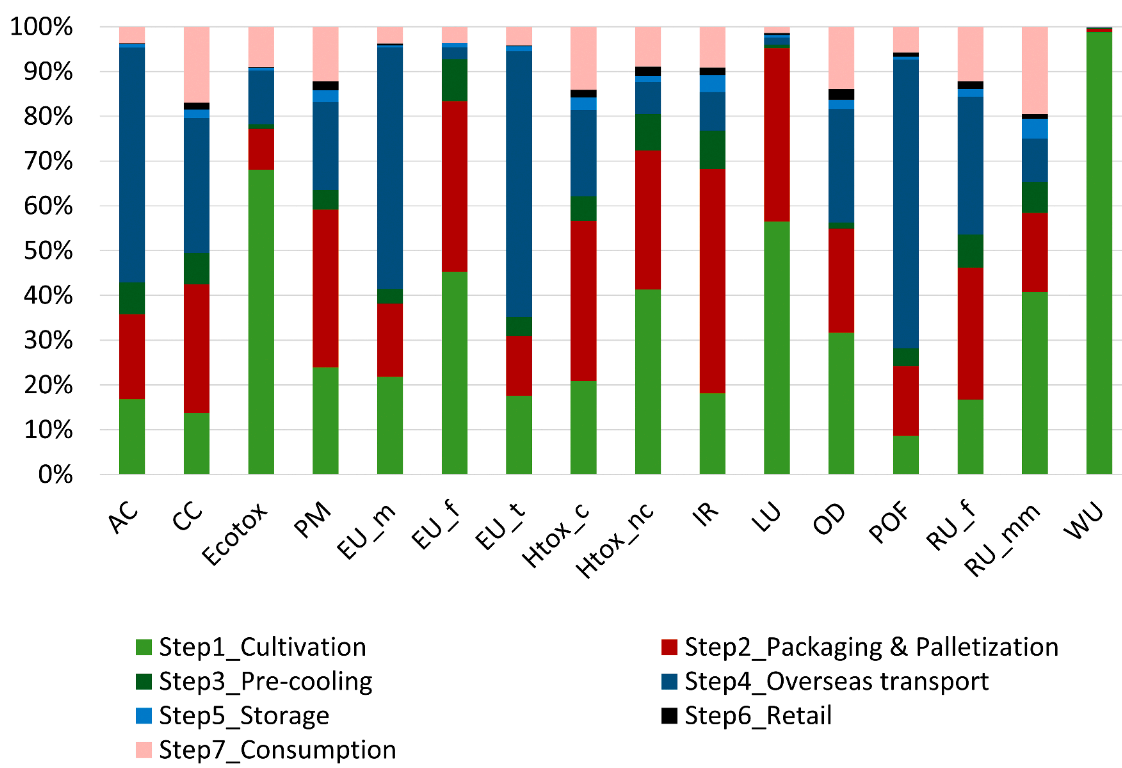

Fig. 2. Contribution to each impact category of the stages from cultivation to final consumption to the environmental impacts of the overall citrus value chain per 1 kg citrus at consumer, expressed on a relative scale. AC = acidification terrestrial; CC = climate change; Ecotox = ecotoxicity, freshwater; PM = particulate matter; EU_*m* = eutrophication, marine; EU_*f* = eutrophication, freshwater; EU_*t* = eutrophication, terrestrial; Htox_*c* = human toxicity, cancer effects; Htox_nc = human toxicity, non-cancer effects; IR = ionising radiation; LU = land use; OD = ozone depletion; POF = photochemical ozone formation; RU_*f* = resource use, fossils; RU_mm = resource use, minerals and metals; WU = water use.

transport itself and the cooling, significantly impact the final environmental impact of the orange supply chain (circa 50 % out of the overall single score impact), thus averagely in line with our findings.

We aggregated the results to assess the environmental impacts of the pre- and post-harvest activities. We identified that 13 impact categories show higher impact in the post-harvest stages, ranging from around 55 % in freshwater eutrophication to circa 91 % in photochemical ozone formation, while the remaining three impact categories present higher results in the pre-harvest stage, i.e. cultivation. This is the result of aggregating the potential environmental impacts of five stages compared to the cultivation stage which alone contributes to the pre-harvest. This shows the relevance of assessing the environmental impacts at various levels of details, not to miss important impact and potential hotspots of impacts to mitigate.

Often, a single score approach using a weighting scheme is used to support decision making and facilitate communication of LCA results. Indeed, weighting helps to identify the most relevant impact categories, and guide decision-makers towards finding the most adequate solutions to reduce the environmental impacts (Sala et al., 2018). Therefore, the potential environmental impacts of the citrus value chain, expressed per 1 kg of consumed citrus, weighted according to the EF 3.1 weighting (see Section 2.3) scheme are reported in Table 2 per each impact category, together with the midpoint results.

The single score results show that the overall citrus value chain impacts mostly affect two environmental indicators: water use and climate change, respectively circa 44 % and 14 % of the overall weighted score, summing up to >50 % (Fig. 3a). Climate change has the highest weighting score, 21.06 %, indicating that this impact category is particularly relevant for the stakeholders behind the development of the weighting scheme, also reflecting the current major societal concerns on the matter. Water use has the third largest weighting score, 8.51 %, after particulate matter, 8.96 %, this latter does not show particular relevance overall (4 % of the whole weighted score). The impacts on water use are almost totally derived from the pre-harvest stage, while impacts on climate change are mostly derived from the post-harvest processes.

Table 2
Environmental impacts of 1 kg citrus at consumer, calculated with the EF 3.1 method at midpoint level and weighted single score. The results are ordered from the impact category with higher to lower relevance according to the weighted result. AC = acidification terrestrial; CC = climate change; Ecotox = ecotoxicity, freshwater; PM = particulate matter; EU_*m* = eutrophication, marine; EU_*f* = eutrophication, freshwater; EU_*t* = eutrophication, terrestrial; Htox_*c* = human toxicity, cancer effects; Htox_nc = human toxicity, non-cancer effects; IR = ionising radiation; LU = land use; OD = ozone depletion; POF = photochemical ozone formation; RU_*f* = resource use, fossils; RU_mm = resource use, minerals and metals; WU = water use.

Impact category	Midpoint impact	Midpoint unit	Weighted results (unit less)	% weighted results
WU	9.41	m3 depriv.	6.97×10^{-5}	44.22 %
CC	7.90×10^{-1}	kg CO2 eq	2.20×10^{-5}	13.99 %
RU_f	9.82	MJ	1.26×10^{-5}	7.98 %
AC	1.05×10^{-2}	mol $H+$ eq	1.17×10^{-6}	7.40 %
POF	7.13×10^{-3}	kg NMVOC eq	8.34×10^{-6}	5.29 %
PM	4.29×10^{-8}	disease inc.	6.47×10^{-6}	4.11 %
EU_t	2.83×10^{-2}	mol N eq	5.92×10^{-6}	3.76 %
RU_mm	4.46×10^{-6}	kg Sb eq	5.29×10^{-6}	3.36 %
Ecotox	1.28×10^{1}	CTUe	4.33×10^{-6}	2.75 %
EU_m	2.82×10^{-3}	kg N eq	4.28×10^{-6}	2.72 %
LU	3.10×10^{1}	Pt	3.01×10^{-6}	1.91 %
HTox_nc	1.56×10^{-8}	CTUh	2.24×10^{-6}	1.42 %
EU_f	4.69×10^{-5}	kg P eq	8.15×10^{-7}	0.52 %
Htox_c	6.40×10^{-10}	CTUh	7.91×10^{-7}	0.50 %
IR	8.18×10^{-3}	kBq U-235 eq	9.72×10^{-8}	0.06 %
OD	1.46×10^{-8}	kg CFC11 eq	1.76×10^{-8}	0.01 %
Total	-	-	1.58×10^{-4}	100 %

When aggregating the weighted results into pre- and post-harvest activities (Fig. 3b), post-harvest shows a lower overall impact, standing at 6.78×10^{-5}, thus covering 46 % of the total weighted single score. On the other hand, pre-harvest processes contribute to higher environmental impacts, 8.11×10^{-5}, representing over half of the total weighted single score. This is the result of combining the significantly high impacts of water use from pre-harvest and the weighting factor (WF) for this impact category, which is the third highest among all WF.

3.1. Sensitivity analysis

A one-way deterministic sensitivity analysis was performed on key inventory parameters to evaluate the influence of data uncertainty on the final impact results. The key inventory parameters were identified through the hotspot analysis as the input flows that contribute significantly to the overall impact: (i) the amount of irrigation water used in the cultivation stage (Stage 1), (ii) the weight of the Supervent paperboard boxes used in packaging & palletization (Stage 2); and (iii) the energy consumption for cooling and keeping a stable, cool temperature during overseas shipment (Stage 4). Each selected parameter was varied individually by ±30 %, while keeping all other parameters constant (Table 2). The ±30 % variation was selected because considered plausible, within the typical range tested in LCA studies. The effect on the total impact result per impact category (midpoint) and on the weigthed impact score was quantified and the parameters were ranked according to their influence. This approach follows commonly used sensitivity procedures in LCA practice (ISO 14044).Table 3

The complete results of the sensitivity analysis are presented in detail in the SM. In general, adjusting the three selected parameters does not produce substantial changes in the overall environmental impacts, either at the midpoint level or in the aggregated weighted score. The main patterns observed in the baseline scenario are largely maintained.

At the midpoint level, varying the irrigation water use in Stage 1 by −30 % causes only a minor shift in the hotspot ranking: the impact category human toxicity- cancer effect moves from being the second-largest contributor to the third, while no change is observed under the +30 % scenario. This indicates a limited sensitivity of this stage to irrigation water assumptions. For Stage 2, altering the weight of the Supervent paperboard box results in more visible changes. When the box weight is reduced by 30 %, the ecotoxicity freshwater category moves from third to fourth in the hotspot ranking. Moreover, for climate change and resource use- fossils, Stage 2 becomes the dominant hotspot (1st place) instead of the second, and for ozone depletion, Stage 2 shifts from the third to the second position. In Stage 4, modifying the energy required for cooling and maintaining stable temperatures during overseas shipment leads to results broadly consistent with the baseline scenario, except again for climate change and resource use- fossils, where slight shifts in the ranking occur. Across all scenarios, the combined contributions of Stages 1, 2, and 4 remain consistently high, accounting for at least 66 % of the total impacts across all impact categories (compared to 68 % in the baseline).

Regarding magnitude of change, the average variation in final impact results is around ±2 % for most categories, with Stage 2 showing the greatest sensitivity, reaching variations up to ±10 %. This indicates that the weight of the Supervent paperboard box is the most influential of the three parameters tested Fig. 4

Across all sensitivity scenarios, the relative distribution of impacts between the pre-harvest and post-harvest phases remains largely unchanged. On the weighted score level, the pre-harvest stage consistently accounts for a slightly larger share of the total environmental burden, contributing approximately 55–57 % of the overall impact. The post-harvest stage, in comparison, represents about 43–45 %, which is very close to the proportions observed in the baseline scenario. This indicates that the balance of impacts along the value chain is stable, even when the selected parameters are varied.

Overall, the sensitivity analyses demonstrate that the results of the

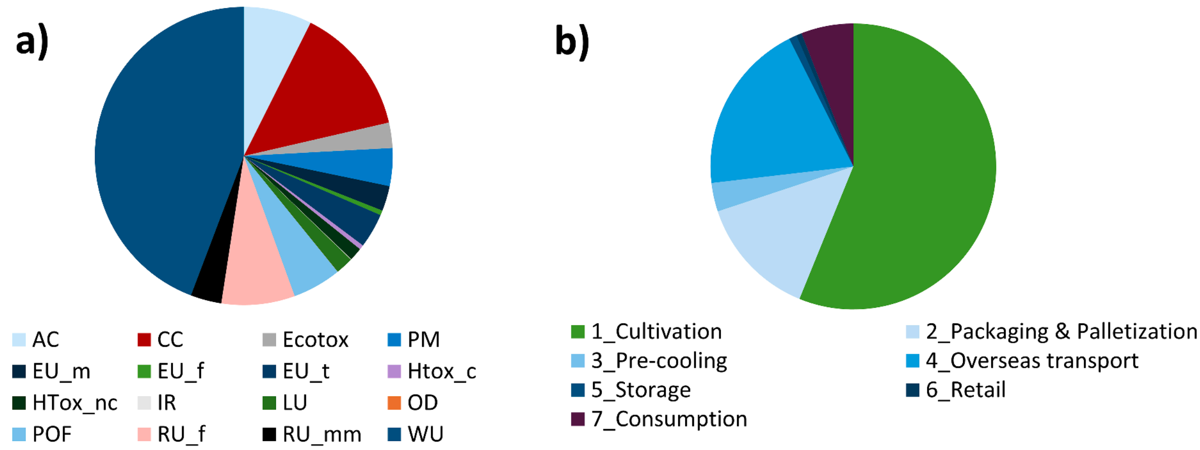

Fig. 3. Contribution of each impact category (a) and of pre- and post-harvest respectively in green and blue (b) to the overall weighted environmental impact of the citrus value chain, expressed on a relative scale. AC = acidification terrestrial; CC = climate change; Ecotox = ecotoxicity, freshwater; PM = particulate matter; EU_*m* = eutrophication, marine; EU_*f* = eutrophication, freshwater; EU_*t* = eutrophication, terrestrial; Htox_*c* = human toxicity, cancer effects; Htox_nc = human toxicity, non-cancer effects; IR = ionising radiation; LU = land use; OD = ozone depletion; POF = photochemical ozone formation; RU_*f* = resource use, fossils; RU_mm = resource use, minerals and metals; WU = water use.

Table 3
Key inventory parameters and their values, used in the sensitivity analyses.

Life cycle Stage	Parameter	Unit	Baseline Value	Low Value	High Value	Justification
1	Irrigation water amount ("market for irrigation, ZA" from ei v.3.9.1)	m3/ kg fresh citrus produced	0.234	0.164	0.305	Data uncertainty 30 %
2	Weigth of paperboad box	kg / kg packed citrus	0.075	0.052	0.097	Data uncertainty 30 %
4	Energy consumption for cooling and keeping a stable, cool temperature during overseas shipment	MJ / lg cool packed citrus	0.421	0.295	0.547	Data uncertainty 30 %

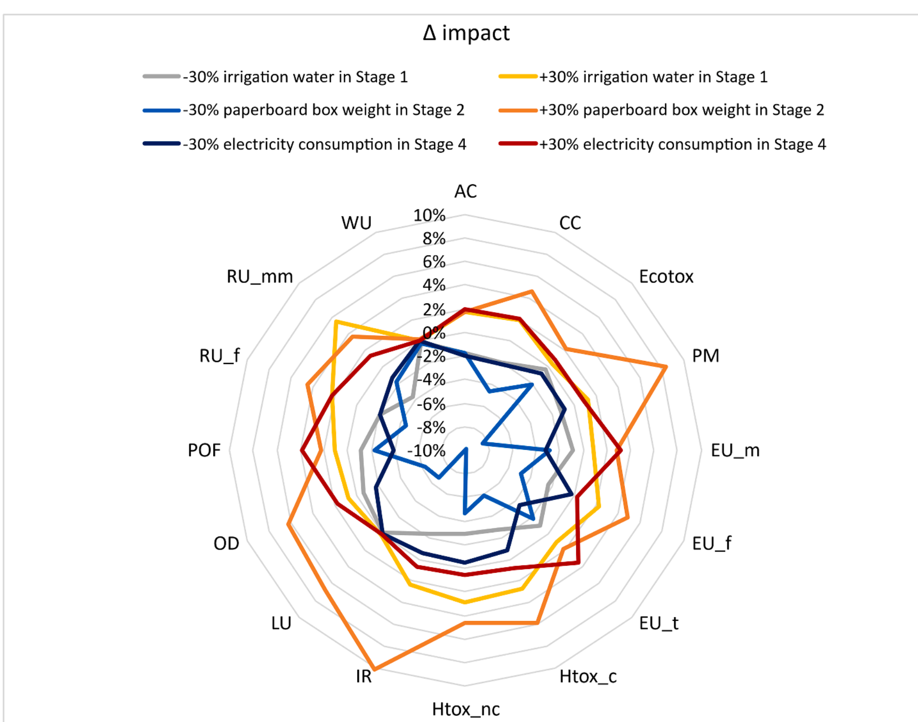

Fig. 4. Variation of impact results for each impact category compared to the baseline case study. AC = acidification terrestrial; CC = climate change; Ecotox = ecotoxicity, freshwater; PM = particulate matter; EU_*m* = eutrophication, marine; EU_*f* = eutrophication, freshwater; EU_*t* = eutrophication, terrestrial; Htox_*c* = human toxicity, cancer effects; Htox_nc = human toxicity, non-cancer effects; IR = ionising radiation; LU = land use; OD = ozone depletion; POF = photochemical ozone formation; RU_*f* = resource use, fossils; RU_mm = resource use, minerals and metals; WU = water use.

study are robust. The variations applied to the three parameters lead to only minor shifts in impact magnitudes and hotspot rankings, suggesting that the assumptions related to these data points do not substantially influence the final outcomes of the LCA. Therefore, these parameters can be considered less critical for further data refinement or model improvement. Other factors that were not tested here—such as the proportion of food loss and waste along the value chain—may be worth of further examination, although they do not stand behind any hotspot of impacts highlighted from this study.

4. Discussion

Based on the consumption of 1 kg of orange in the Netherlands, our LCI covers seven stages of the intercontinental citrus value chain, accounting for primary and secondary packaging material, infrastructure, energy consumption and different types of waste treatments, where waste is generated. In contrast to the study that served as the foundation for our research (Wu et al., 2019), our work expands the value chain by including the pre-harvest and consumption stage and assessing the environmental impacts for 16 different indicators. We have also provided a more in-depth analysis of the stages, especially packaging, which significantly contributes to environmental impacts throughout the entire value chain. Our study disclosed the environmental impact of each stage and process, comparing pre-harvest and post-harvest processes, and highlighting the main hotspots of impacts.

By applying the weighting scheme, thus obtaining a single score for the environmental impact of the citrus value chain, we observed that the cultivation (pre-harvest) phase contributed to the environmental impact of the citrus value chain by 56 % while that of the post-harvest supply chain impacted the environment by 44 %. This result is given by the combination of the type of data (average or punctual) used in this specific case study and the weighting system. Overall, our findings demonstrate that environmental burdens associated with citrus consumption extend well beyond the cultivation stage. While the weighted single-score results indicate that the difference between pre- and post-harvest impacts is not substantial (approximately 20 %), both phases contain clear hotspots that merit attention. In particular, cultivation, packaging-and-palletization, and overseas refrigerated transport collectively account for at least 68 % of the overall environmental impact across all categories. This highlights that mitigation strategies focusing solely on agricultural improvements would overlook substantial emissions arising later in the value chain. Therefore, a more effective sustainability strategy must also address the energy-intensive nature of cold-chain logistics, packaging processes, and intercontinental distribution. Potential improvement measures include enhanced water management during cultivation, process optimization in the export cold-chain to minimize energy consumption, the decarbonization of transport modes or shortening of export routes, and improved digital monitoring to reduce food loss and waste during transit. These insights help identify the key stakeholders including producers, exporters, logistics operators, retailers, and policymakers, who can contribute to reducing the environmental impacts of citrus supply chains and support progress toward EU sustainability objectives.

Concerning policymakers in particular, the dominance of post-harvest processes, with higher impacts in 13 out of 16 impact categories, has direct relevance for EU efforts to decarbonize food systems. This finding aligns with key policy frameworks, including the European Green Deal, the Farm-to-Fork Strategy, and ongoing Horizon Europe actions that support the development of low-carbon and energy-efficient cold-chain logistics (CEC 2020; EC, 2023; WWF and Climate Focus, 2024). The European Commission has emphasized the need to reduce emissions from food refrigeration, transport, and logistics through measures such as the deployment of energy-efficient and low-GWP refrigeration technologies, modal shifts toward lower-emission freight transport, including optimized maritime logistics. Additional priority measures include the adoption of sustainable packaging and circular bio-based materials, and improvements in digital cold-chain monitoring to reduce spoilage and energy waste (reflected in EU cold-chain sustainability initiatives and Commission programs on sustainable food logistics). Our results support these policy priorities by demonstrating that mitigation efforts in post-harvest logistics could achieve greater overall reductions than interventions targeted solely at cultivation; therefore, investments in cold-chain decarbonization, packaging innovation, and optimized intercontinental logistics are crucial to reducing the environmental burden of imported citrus and other perishable fruits. Weighted single-score results reinforce this conclusion, confirming the need for system-wide interventions rather than farm-level improvements alone. While post-harvest measures appear particularly decisive in this context, our findings do not diminish the importance of pre-harvest interventions, which remain essential for soil, water, and biodiversity outcomes and should be pursued in parallel with logistics decarbonization.

Beyond the alignment with EU policy frameworks, our findings also directly support the ambitions of the United Nations Sustainable Development Goals, particularly SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). SDG 12 calls for reducing food loss and waste and improving the sustainability of global value chains, while SDG 13 urges rapid decarbonization across all sectors, including food system logistics. By identifying post-harvest cold-chain operations and intercontinental transport as dominant contributors to environmental impacts, our study provides evidence that can inform strategies to reduce resource use, minimize food loss, and lower greenhouse-gas emissions across the citrus supply chain. As such, the measures discussed, ranging from packaging innovation and logistics optimization to the deployment of low-carbon refrigeration technologies, represent actionable pathways to advance progress toward both SDG 12 and SDG 13.

At the same time, citrus value chains are complex systems in which phases are interconnected and multiple actors influence overall performance. Agronomic practices shape fruit quality and yields, affecting post-harvest handling requirements, while resource inputs during cultivation, such as energy, water, and fertilizer use, have implications for the intensity and design of logistics operations. Packaging waste and other losses generated during post-harvest activities can also be traced back to decisions made earlier in the chain. A holistic view is therefore needed to ensure that improvement strategies in one stage do not generate unintended burdens in another. Coupling LCA outcomes with other sustainability dimensions, such as economic feasibility via life cycle costing (LCC), may offer additional insights into the trade-offs and constraints affecting implementation.Therefore, inventory data and results of this LCA study can serve as a starting point to develop a “monitoring tool” of environmental impacts for all the stakeholders across the citrus value chain. The underlying model is structured in a simplified way and can be filled in directly by the value chain actors with their own data, to improve the representativeness of the value chains’ stages, and possibly enhance communication and cooperation between stakeholders in different stages of the value chain towards better environmental sustainability. Indeed, stakeholders across the entire value chain could identify and concentrate on processes within specific stages that could be optimized to enhance environmental sustainability. Additionally, the LCA model of our study can be integrated into a digital replica of the citrus supply chain. This can also include an existing monitoring system with an additional dashboard (e.g., “Environmental impact dashboard”) to dynamically display the environmental impact of the different stages of the value chain in real-time. This could also be coupled with methodologies covering other sustainability dimensions, such as life cycle costing (LCC) analysis.

Besides its strengths, it is important to highlight the limitations of the inventory data we modeled and the LCA study performed. Although the ecoinvent dataset we used for the cultivation stage refers to the production of oranges in South Africa and is built with in-field collected data, the dataset reports average data which might differ from one specific farm to another. Furthermore, as highlighted in Martin-Gorriz et al. (2020), the LCA results for the cultivation step can change depending on whether the data correspond to a particular (e.g. peak or low production) rather than to an average year. In this study, the yield considered is the average yield per ha in 2015. This highlights the need to improve the geographical specificity and data coverage, as recommended e.g. in Cabot et al. (2022). Additionally, the use of data from different years (2015 vs. 2022–2024) might cause temporal inconsistencies, as well as the omission of loss rates in pre-cooling and overseas transport stages, might increase the uncertainty of this analysis.

Concerning overseas transport, LCA results are affected by the specific cooling conditions during the shipment, for which we analyzed a single scenario. Therefore, it is advisable to re-calibrate the LCA model for specific supply chains to reflect their real conditions. With the procedure that we applied, we could ideally calculate the energy consumption at different temperatures and shipment lengths and, therefore a more specific environmental impact depending on the citrus (or other fruit) value chain; a validation with measured data is advisable. The uncertainty of data in other steps depends on the fact that data from literature and related estimates were used, especially for defining the share of waste, instead of data collected from real-life cases. Supply chain experts validated some data, but the rest still comes from literature. Actors could directly intervene in complementing and validating data that suit their production conditions and help improve the reliability of the LCA results.

Finally, to achieve sustainable food value chains, we need to model a broader range of value chains and dynamically model the LCI to include real-time food loss and energy consumption elements. In this study, we focused on the intercontinental citrus value chain from South Africa to the Netherlands, serving as an exemplary case study, mainly based on the previous knowledge of the authors and the availability of information. However, this is not representative of all fruit value chains due to significant variations in cultivation practices among farms and geographical locations, climate variability, biological diversity, differences in cold chain infrastructure, shipment routes, and the countries involved in the trade, which in turn affect the assessment of the environmental performance of the whole value chain. Despite these variations, our LCA modelling approach facilitates easy adaptation to different fruit value chains.

5. Conclusions and outlook

The increasing production and consumption of food, especially fruit and vegetables, is posing a risk to the environment and food security. Fruits such as citrus, which have intercontinental value chains, could pose significant environmental sustainability risks. Achieving a sustainable food system that is aligned with SDG 12, requires a comprehensive understanding of global environmental impacts. Life Cycle Assessment serves as a quantitative methodology to facilitate this transition towards increased environmental sustainability.

In this study, we investigated the ecological hotspots of impacts from cultivation to plate of consuming 1 kg of oranges using LCA. We reached a twofold goal. First, we improved the inventory data for the LCA of the entire citrus value chain. The scope covers seven stages, from cultivation in South Africa to consumption in the Netherlands and incorporates more recent data validated by industry experts. Second, we identified hotspots of the impact for 16 environmental indicators, going beyond a focus on the global warming potential only. The key conclusions from our study are as follows:

- Three stages (i.e., cultivation, packaging and palletization, and overseas shipment) contribute the most to the environmental impacts of the intercontinental citrus value chain, covering at least 68 % of the total impact per impact category.
- Water use and climate change are the most affected impact categories, with distinct contributions from pre-harvest and post-harvest processes.
- Cultivation dominates water use impacts (99 %), driven by irrigation, and freshwater ecotoxicity (68 %), due to pesticide and chemical use, followed by land use (57 %).
- Overseas shipment, reliant on energy-intensive cold chains, contributes the most to photochemical ozone formation (62 %) and a significant share of climate change impacts (27 %).

These findings provide critical insights for stakeholders across the citrus value chain. Farmers should prioritize water-efficient irrigation technologies and reduced chemical inputs to mitigate water use and ecotoxicity impacts. Logistics managers and exporters can focus on optimizing refrigerated transport, adopting low-carbon shipping solutions, and improving energy efficiency to address photochemical ozone formation and climate change. Retailers and packaging suppliers should explore sustainable packaging alternatives, such as recyclable or lightweight materials, to reduce the environmental burden of palletization. These targeted actions enable quantifiable reductions in the environmental footprint of citrus production and distribution.

Despite these contributions, the study is constrained by limited granular data and the exclusion of economic and social sustainability dimensions. Future research should enhance the LCI by incorporating measured, geographically specific data and engaging a broader range of stakeholders, including growers, shippers, and retailers, to validate and refine the model. Integrating economic and social indicators into the LCA framework will provide a more holistic assessment, supporting the development of sustainable policies and practices for the global fruit and vegetable value chain.

Declaration of generative AI and ai-assisted technologies in the writing process

During the preparation of this work, the author(s) used Grammarly and Chat GPT to improve the spelling, grammar, and style of the text. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

CRediT authorship contribution statement

Eleonora Crenna: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Roland Hischier:** Writing – review & editing, Supervision, Methodology, Funding acquisition. **Thijs Defraeye:** Writing – review & editing, Project administration, Methodology, Funding acquisition, Conceptualization. **Daniel Onwude:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.envc.2025.101396.

Data availability

Data will be made available on request.

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