Ecological hotspots of the journey of a South African citrus fruit

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Abstract

The global increase in production and consumption of food, particularly fruits and vegetables, poses significant threats to the environment and food security. The increased food production has led to an increased use of resources such as land, water, and fossil fuel for cultivation. Furthermore, the yearly 30% global post-harvest losses and waste of fruits and vegetables represent a significant water and energy loss, thereby contributing to global greenhouse gas emissions. Amidst these concerns, the environmental impact of fruit and vegetables value chain, particularly the transcontinental cold chain, is gaining attention but remains largely unexplored. Using the Life Cycle Assessment methodology, this study addresses the environmental impact of the intercontinental value chain of citrus, chosen as a representative product. We aim to complement the existing life cycle inventory models and provide a comprehensive analysis of the ecological hotspots of environmental impacts of the citrus value chain, from its origin in South Africa to its destination in the Netherlands. The results reveal that cultivation contributes up to ~99% to the environmental impact of water use and to 68% to the environmental impacts associated with freshwater ecotoxicity. In the post-harvest stages, overseas shipment contributes 62%, to the impact of photochemical ozone formation, followed by circa 52% to the impact of marine eutrophication. The production of cardboard boxes, used to transport citrus fruits from the packaging house until the retailer, shows generally the second highest impact scores among the post-harvest stages. Through the analysis of a weighted single score, the pre-harvest activities emerge as the main contributor to the overall weighted environmental impact of the citrus value chain, standing at 56%, primarily due to irrigation and chemical usage. Despite limitations concerning the use of average or punctual data for certain processes, our data model and its subsequent analysis represent a starting point in assessing the environmental sustainability of intercontinental fruit and vegetable value chains. Hence, this work establishes a valuable basis for developing a digital twin as a monitoring tool for supply chain stakeholders, adaptable to different fruit and vegetable value chains, thus facilitating the identification of stage-to-stage environmentally sustainable practices.

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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)

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 & Gomez-Zavaglia, 2022; Springmann et al., 2022; Xu & 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. About one-third of the world's fruits and vegetables are lost or wasted annually along the entire food value chain (Bellù, 2017; Bancal & 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 55 billion tons of CO_2 equivalent in 2021 (Ritchie et al., 2020). Therefore, there is an urgent need to unveil the overall environmental impacts of the global food system, including that of fruits and vegetables. Such quantification and insight are vital in achieving a sustainable food value chain, ensuring food security and reducing food loss, as part of the *United Nations Sustainable Development Goals under (SDG) number 12, "responsible production and consumption".*

Amid growing global concerns regarding the environmental consequences of food production and consumption, the European Union (EU) has implemented targeted policies. 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. A well-known example is represented by citrus. 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 cultivation 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). All these steps contribute to greenhouse gas emissions, with citrus fruits alone accounting for over ~15% of global fresh food production (FAO, 2022). 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).

Several LCA studies investigated thoroughly the environmental impacts of citrus cultivation in different regions, e.g. Italy (Falcone et al., 2019), Spain (Martin-Gorriz et al., 2020), Nigeria (Ogunlade et al., 2020), Mexico (Bonales-Revuelta et al., 2022). Hence, the environmental impact on the local supply chain must be examined. Little attention has been devoted to understanding the consequences of citrus post-harvest processing and export to other countries on various environmental factors, including not only greenhouse gas emissions, but also water and land usage among others. For instance, the work by Wu et al. (2019) calculates the carbon footprint of the citrus post-harvest cold chains, although did not focus on aspects like freshwater impact, land use, and water usage. Moreover, studies rarely accounted for the individual contribution of the processes comprising various stages of the fruits and vegetables value chain. Understanding these overlooked dimensions, examining as well aspects like packaging, transportation and end-of-life implications, which are scarcely addressed in the existing literature ((Pernollet et al., 2017; Cabot et al., 2022, du Plessis et al., 2022) is essential for a comprehensive assessment of the environmental impact within the global fruit and vegetable value chain and to advance the shift towards environmentally sustainable food production and consumption systems.

To fill the identified gaps based on the methodological recommendations in Cabot et al. (2022), this study aims to carry out a full LCA on the transcontinental citrus supply chain by: (i) extending the modeling of the life cycle inventory (LCI) of the various steps from the pre-harvest growing activities in South Africa to the transcontinental post-harvest supply chain to the Netherland of citrus, chosen as exemplificative fruit, and (ii) identify ecological hotspots of impacts across 16 environmental indicators.

South Africa is the world's second-largest citrus exporter, trailing only behind Spain, contributing to 10% of global citrus exports (Chisoro & 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; ISO, 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 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 Figure 1.

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

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 on 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 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 formula 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 7,500 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 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 & 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.

2.2.4 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 & 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 1,824,900 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.

2.2.7 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 & Pant, 2019; EC-JRC, 2022) was used as the LCIA method of choice. 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 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.

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}

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)
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}

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 Figure 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.

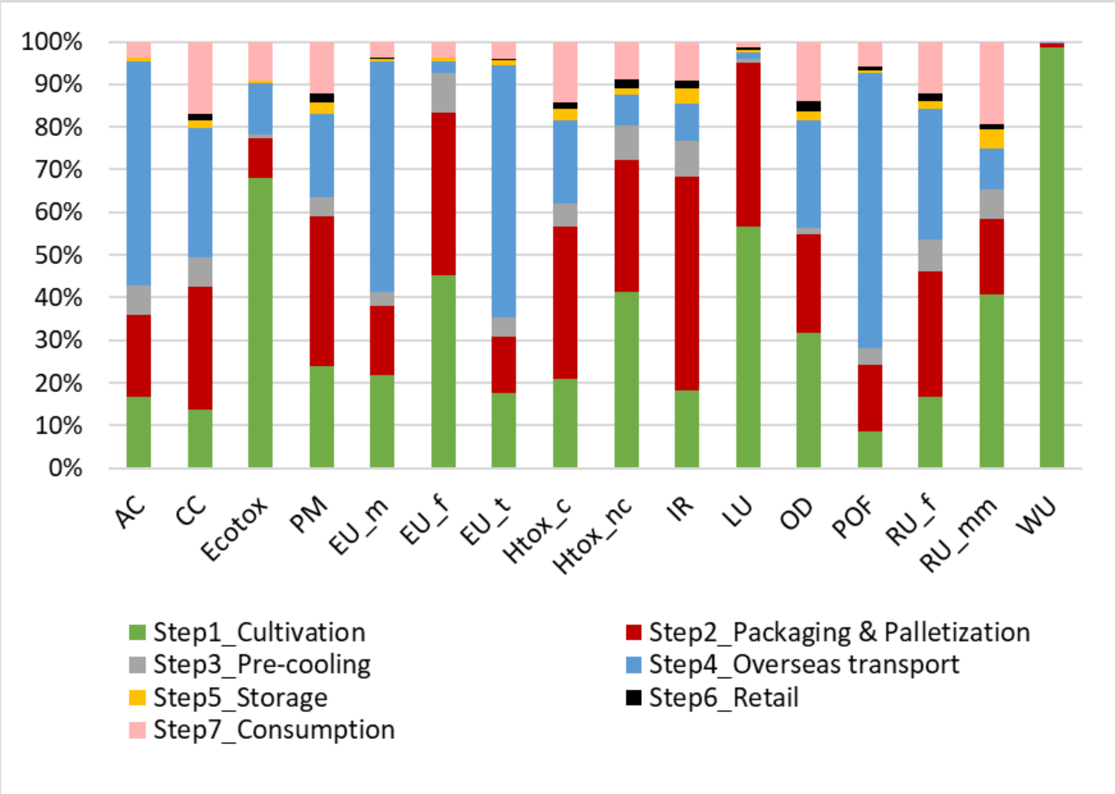

Figure 2. Contribution to each impact category of the stages from cultivation to final consumption to the environmental impacts of the overall citrus value chain per 1 kg citrus at consumer, expressed on a relative scale. AC = acidification terrestrial; CC = climate change; Ecotox = ecotoxicity, freshwater; 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.

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 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.

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.

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%

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% (Figure 3 a). 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.

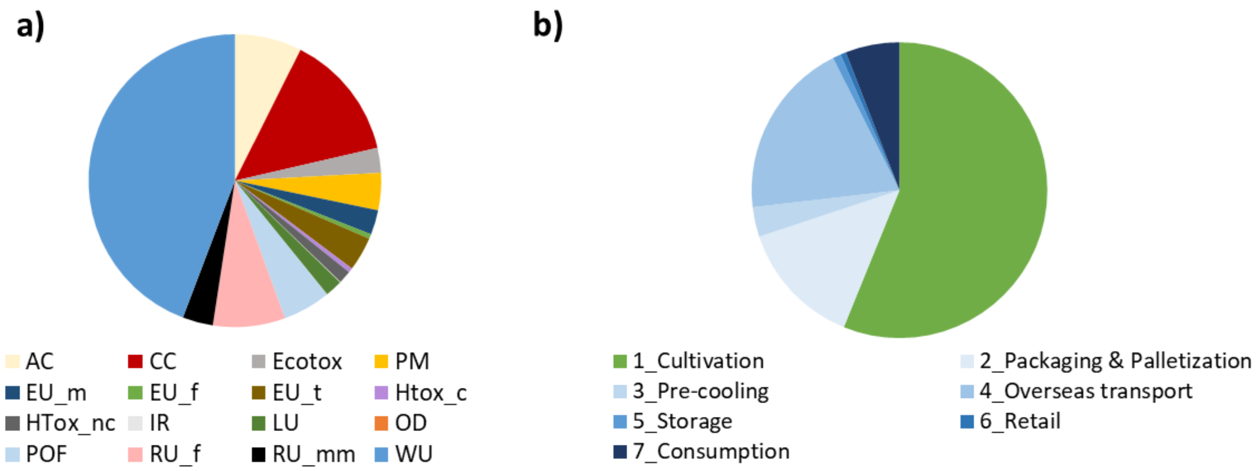

Figure 3. Contribution of each impact category (a) and of pre- and post-harvest respectively in green and blue (b) to the overall weighted environmental impact of the citrus value chain, expressed on a relative scale. AC = acidification terrestrial; CC = climate change; Ecotox = ecotoxicity, freshwater; 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.

When aggregating the weighted results into pre- and post-harvest activities (Figure 3 b), 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.

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, based on our model, the difference between the environmental impacts of the pre-harvest and the post-harvest phase is not significantly high (around 20%), and both phases involve processes that deserve attention. Indeed, we identified the cultivation, packaging-and-palletization, and overseas transport stages to be responsible for most environmental impacts across the citrus value chain, altogether contributing to at least 68% of the overall impact in each impact category. The outcomes of our LCA underscore the significance of addressing improvements in both pre- and post-harvest phases, for instance, by identifying potential solutions for water management during cultivation, and for process optimization in the export cold-chain by minimizing energy consumption, while monitoring the food quality and reducing waste along the route. These findings already help identify the possible stakeholders who can contribute to taking up such actions to mitigate the impacts.

Nevertheless, such value chains are complex systems where the various phases are interconnected, and multiple stakeholders are involved. The quality of cultivation practices affects the yield and quality of harvested citrus. Better cultivation practices lead to higher-quality fruit. Additionally, energy, water, and material inputs during cultivation directly impact the post-harvest phase. For instance, efficient irrigation during cultivation affects water availability for post-harvest processes. Furthermore, waste generated during post-harvest activities (e.g., packaging waste) can be traced back to cultivation practices. Analyzing the impact of pre- and post-harvest value chains provides a holistic view of the citrus value chain's environmental impact.

Due to such complexity, it becomes relevant to couple the LCA outcomes with the analysis of other sustainability dimensions, such as the economic one, in order to identify not only potential improvements based on ecological hotspots of impacts, but also economic constraints that might prevent implementing such sustainable practices.

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 possible 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).

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 modeling 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.

- The impact categories related to water use and climate change are the most affected; a difference in effects can be seen between pre-harvest and post-harvest processes.
- Cultivation has the highest impact on water usage (WU, 99% of the total impact for this category), because of irrigation, as well as on ecotoxicity freshwater (Ecotox, 68%), attributed to the use of pesticides and other chemicals. Land use (LU, 57%) follows closely in terms of impact.
- The energy consumption along the cold chain, especially during the overseas shipment from South Africa to Europe, contributes the highest impacts on photochemical ozone formation (62%), and a good portion of climate change (circa 27%).

These findings are significant as they enable quantifying environmental impacts associated with the production, processing, distribution and consumption of citrus through a cold store. Nevertheless, this study is limited by the lack of granular data and other sustainability dimensions such as economic and social aspects. Future research endeavors should focus on enhancing the life cycle inventory by engaging a broader spectrum of stakeholders. This involves incorporating measured and geographically specific data to validate our approach. There is also a need to explore the integration of the LCA with other assessment tools, to cover the various dimensions of sustainability and with a digital twin of a food value chain, to provide more comprehensive insights thus being able to identify stage-to-stage interventions while ensuring the functioning of the supply chain.

AUTHOR CONTRIBUTIONS

EC: Conceptualization, Methodology, Investigation, Writing Original draft, Review & Editing**;** **RH**: Methodology, Review & Editing; **TD**: Conceptualization, Review & Editing; **DO:** Conceptualization, Methodology, Investigation, Writing Original draft, Review & Editing.

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