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Life cycle assessment of bananas, melons, and watermelons from Costa Rica

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ABSTRACT

Banana and watermelon are the two most important fruit crops in the world, and Costa Rica is one of the leading producers worldwide. Even though the importance of banana, melon, and watermelon crops, few life cycle assessments have been done and published. This study aims to provide information on the environmental performance of the banana, melon, and watermelon sectors in Costa Rica to determine the most significant parameters in the life cycle of these fruits. The supply chain of the fruit crops was analyzed as follows: farm production, post-harvest treatment and packaging, distribution and retail, household consumption, and end of life. It means that the study was developed with a cradle-to-grave approach. The functional unit was 1 kg of fresh fruit delivered in a country of the European Union. Mainly, primary data were used from farms with a conventional farming system. The fruit production process was modeled in SimaPro 9.0. ReCiPe midpoint (H) was used for the impact assessment, where 11 impact categories were evaluated, including the categories required in the product category rules for fruits and nuts. In all three fruit crops studied, the most impact stages are farm production, distribution and retail (international transport), and the end-of-life stage. In this study, waste management is relatively high due to the high amount of the non-edible part of the fruit (38.6 % for bananas and 42 % for melon and watermelon). It has a significant influence on the toxicity impact categories. The carbon footprint for the banana supply chain was estimated at 0.805 kg CO_2-eq/kg of bananas produced in Costa Rica and consumed in Europe, and for melon and watermelon was 0.822 kg of CO_2-eq/kg. Since there are no life cycle assessments of banana fruit with a cradle-to-grave approach, and only studies focused on carbon footprint or with a cradle-to-gate approach are available, more studies and collection of information in situ are necessary.

1. Introduction

The production and consumption of fruits and vegetables have increased steadily. As consumers are becoming more and more informed about food, health, and nutrition issues, they are also becoming aware of the benefits of including fruits and vegetables in their daily diet. For example, the European Union (EU) consumption monitor report shows that 2021 daily fresh fruit and vegetable consumption was 364.58 g per capita. While still below the World Health Organization (WHO) recommended minimum daily consumption (400 g), this represents a 5.1 % increase compared to the previous five years (2013–2017) (Freshfel, 2023). Today, food production is associated with significant environmental problems. For example, agriculture is the second economic sector with more emissions (12 %), only overcome by the energy sector (66 %) (FAO, 2017). In addition, agriculture is the sector with the largest requirements for water and land and the main driver of land use change. The Haber–Bosch process, which is the primary industrial process for the production of fertilizers, disrupts the nitrogen cycle because the nitrogen extracted from the air is larger than all natural processes that require nitrogen and its subsequent application in fertilizer form, resulting in extensive nitrogen emissions to surface water (Dijkman et al., 2018). Considering these antecedents, the growing population, and the increase in the consumption of fruits and vegetables, innovative strategies are needed to ensure that the increase in food production does not negatively affect the environment. If there are no changes in how we produce and consume food, and considering the need to increase food production, the environmental impacts associated with agri-food systems will worsen and potentially exceed planetary boundaries (Notarnicola et al.,

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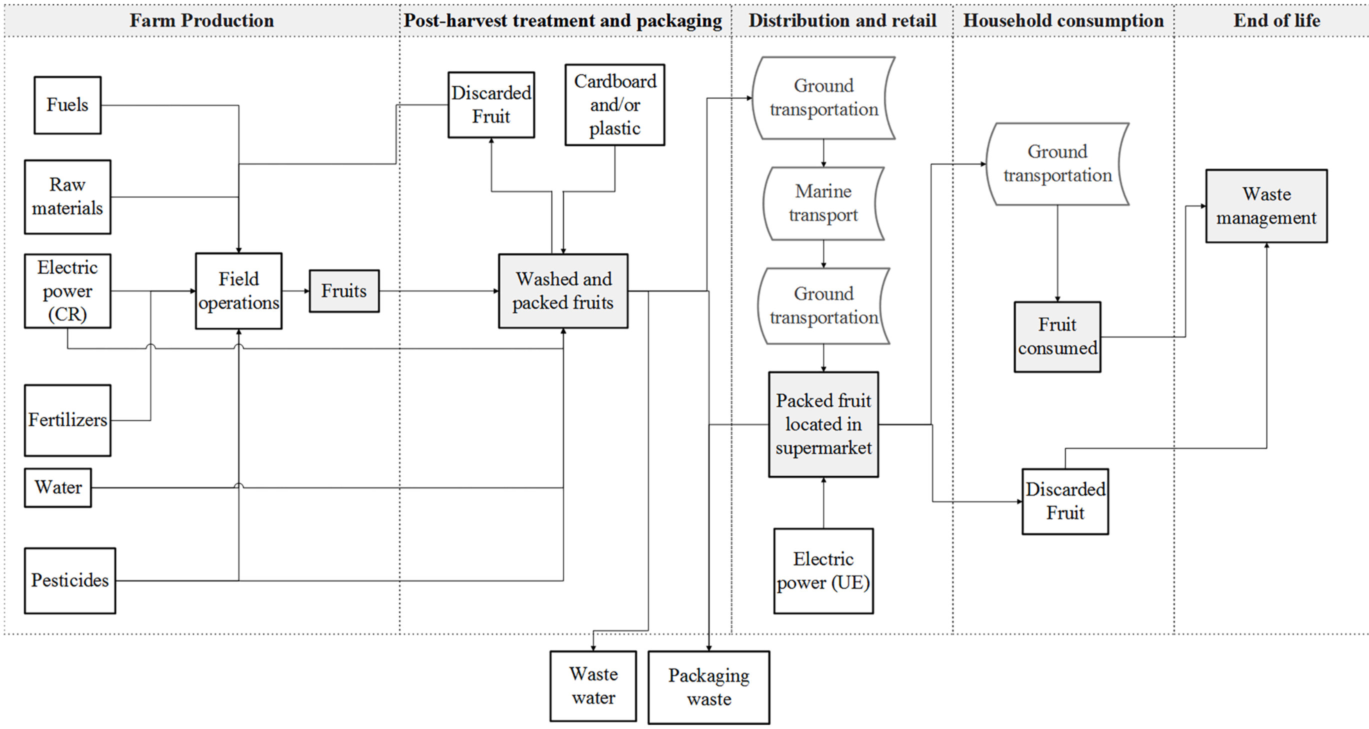

Fig. 1. Life cycle system of fruit production (banana, melon, and watermelon).

2017).

The intention to improve food production and consumption systems is the core of every discourse on sustainable development (Cerutti et al., 2014). With the COVID-19 pandemic and the Russia – Ukraine war, the need to transform and rebalance how food is produced and consumed has only been further stressed. On the other hand, it is impossible to improve something that has not been measured. Therefore, the life cycle assessment (LCA) methodology allows to make informed decisions towards more sustainable food systems, and it is a standardized methodology considered as a requisite for certifications such as Environmental Product Declarations (EPD), eco-labels, and the development of green public procurement.

Banana and watermelon are the two most important fruit crops in the world. In 2021, the production reached 125 and 101 million tons, respectively, which means that these are the two most consumed fruits globally (FAO, 2021). Costa Rica is an upper-middle-income country that bases its economy on industry, services, and agriculture (Ministerio de Hacienda - República de Costa Rica, 2020). Costa Rica is the third largest exporter of bananas, preceded by Ecuador and the Philippines (FAO, 2019). In Costa Rica, banana cultivation is concentrated in the Atlantic region of Limón which experiences a tropical humid climate and covers an area of 47,750 ha are. In contrast, melons/watermelons are primarily grown in the tropical dry regions of the Nicoya Peninsula and Puntarenas, with 4437 ha and 3228 ha cultivated, respectively. The main export markets for these crops are the United States of America and the European Union (PROCOMER, 2021). In this study, The Netherlands is considered the country of fruit consumption, as it is one of the primary importers of Costa Rican melons, watermelons, and bananas. Additionally, Costa Rica is recognized globally for its environmental policies and achievements, which have helped the country build its "Green Brand" (The World Bank, 2020).

To the best of our knowledge, few life cycle assessments have been done and published despite the importance of banana, melon, and watermelon fruit crops (Azizpanah et al., 2023; Coltro and Karaski, 2019; Mohammadi-Barsari et al., 2016; Veliz et al., 2022). In other studies, the analysis is limited to the carbon footprint (Craig et al., 2009; De Figueirêdo et al., 2013; Iriarte et al., 2014; Roibás et al., 2016; Stoessel et al., 2012; Svanes and Aronsson, 2013). This study aims to provide information on the environmental performance of the banana (*Musa paradisiaca* L.), melon (Cucumis melo L), and watermelon (*Citrullus lanatus*) sectors in Costa Rica to determine the most significant parameters in the life cycle of these fruits.

2. Methods

2.1. Goal and scope of the study

This study analyzes the environmental performance of the banana, melon/watermelon supply chain, including farm production, post-harvest treatment and packaging, distribution and retail, household consumption, and end-of-life. It means that the study was developed with a cradle-to-grave approach. The functional unit, defined as the quantified performance of a system for its use as a reference unit (ISO, 2006a), was 1 kg of fresh fruit delivered in a country of the EU.

2.2. System boundaries

The stages and unit processes included in the system were selected based on the Product Category Rules for Fruits and Nuts (The International EPD® System, 2019). Following the PCR, the cut-off criteria establish that all the elemental flows and processes that contribute 99 % of the total impacts must be included, as well as the judgment of experts. Fig. 1 shows the system boundaries considered for the study and its unit processes. The impacts of the wastewater from the fruit washing process and the packaging waste obtained in the packaging plant and at retail are considered to be sent to recycling, so the principle of "the polluter-pays" has been adopted.

2.3. Inventory data and key assumptions

For the studied crops, mainly primary data were used from farms with a conventional farming system, representing 1434 ha of banana and 776 ha of melon and watermelon (373 ha and 403 ha, respectively). The average annual yield in the studied area is 35 t/ha for bananas, 29 t/

Table 1
Global inventory for 1 kg of banana produced in Costa Rica and consumed in the EU.

Stage	Materials	Unit	Value
Farm Production	**Inputs**		
	Natural resources		
	Water	m^3	0.00
	Land use	m^2/year	0.20
	Energy and fuels		
	Diesel	kg	2.12E-03
	Gasoline	kg	1.55E-04
	Jet Fuel A-1 (Naphtha)	kg	7.80E-03
	Raw materials		
	Polyethylene	kg	9.54E-04
	Polypropylene	kg	2.16E-04
	Polyethylene foam	kg	1.28E-04
	Fertilizers		
	N, ammonium nitrate	kg	7.70E-03
	P_2O_5	kg	7.06E-04
	K_2O	kg	8.76E-03
	$CaCO_3$	kg	1.72E-03
	$CaMg(CO_3)_2$	kg	8.21E-04
	Chicken manure	kg	1.04E-03
	Pesticides, herbicides or fungicides		
	Spraytex	kg	2.51E-03
	Mancozeb	kg	1.93E-03
	Buprofezina	kg	6.87E-06
	Bifentrina	kg	9.54E-08
	Total	kg	1.94E-03
	Outputs		
	Banana	kg	1.00E+00
	Polyethylene	kg	9.54E-04
	Polypropylene	kg	2.16E-04
	Polyethylene foam	kg	1.28E-04
	Atmospheric emissions		
	NH_3	kg	1.25E-03
	NO_2	kg	2.56E-04
	N_2O	kg	1.88E-04
	CO_2	kg	1.46E-02
	CH_4	m^3	1.33E-06
	Mineral oil	kg	2.10E-04
	Mancozeb	kg	1.74E-04
	Buprofezina	kg	6.18E-07
	Bifentrina	kg	8.59E-09
	Aquatic emissions		
	N	kg	9.60E-04
	NO_3^-	kg	2.09E-03
	P	kg	6.82E-04
	Mineral oil	kg	2.34E-05
	Mancozeb	kg	1.93E-05
	Buprofezina	kg	6.87E-08
	Bifentrina	kg	9.54E-10
	Terrestrial emissions		
	Mineral oil	kg	2.10E-03
	Mancozeb	kg	1.74E-04
	Buprofezina	kg	6.18E-06
	Bifentrina	kg	8.59E-08
Post-harvest treatment and packaging	**Inputs**		
	Natural resources		
	Banana	kg	1
	Water	m^3	3.01E-03
	Energy and fuels		
	Liquefied petroleum gas	kg	9.09E-05
	Electric power (Costa Rica)	kWh	7.58E-03
	Diesel	kg	5.66E-04
	Raw materials		
	LDPE	kg	6.84E-03
	Corrugated cardboard	kg	2.65E-02
	Chlorine	kg	6.56E-05
	Citric acid	kg	2.74E-05
	Aluminum sulfate	kg	3.43E-05
	Azoxistrobina	kg	1.25E-04
	Imazalil	kg	2.70E-03
	Thiabendazole	kg	7.49E-05

Table 1 (*continued*)

Stage	Materials	Unit	Value
	Total	kg	3.17E-04
	Outputs		
	Packed banana	kg	1.03
	Atmospheric emissions		
	N_2O	kg	8.60E-08
	CO_2	kg	6.23E-04
	CH_4	kg	1.70E-07
	Azoxistrobina	kg	1.12E-05
	Imazalil	kg	2.43E-04
	Thiabendazole	kg	6.74E-06
	Aquatic emissions		
	Wastewater	m^3	2.14E-03
	Azoxistrobina	kg	1.25E-06
	Imazalil	kg	2.70E-05
	Thiabendazole	kg	7.49E-07
	Terrestrial emissions		
	Azoxistrobina	kg	1.12E-04
	Imazalil	kg	2.43E-03
	Thiabendazole	kg	6.74E-05
Distribution and retail	**Inputs**		
	Electric power (Costa Rica)	kWh	0.020
	Transport, freight, sea, transoceanic ship with reefer, cooling	t.km	9.17
	Packed banana	kg	1.03
	Electricity, high voltage, production mix | electricity, high voltage | Cut-off, S – NL	kWh	0.02
	market group for electricity, low voltage | electricity, low voltage | Cut-off, S – RER	kWh	0.02
	Transport, freight, lorry > 32 t, EURO 4	t.km	0.08
	Ethylene	kg	3.70E-04
	Freon gas (R404a)	kg	1.10E-04
	Outputs		
	Banana	kg	1
	Corrugated cardboard	kg	0.03
	Ethylene	kg	3.70E-04
	HFC - 125	kg	1.10E-04
Household consumption	**Inputs**		
	Banana	kg	1
	Transportation in a light commercial vehicle	km	0.185
	Plastic bag LDPE	kg	0.0025
	Water	m^3	8.80E-04
	Outputs		
	Solid residues	kg	0.386
	Water	m^3	8.80E-04

ha for melons, and 39 t/ha for watermelons. An average yield of 34 t/ha was used for the latter two crops. Data were collected in 2020, so it refers to the productive cycle of the year 2019. It is essential to highlight the year of data because it is well known that between years, the environmental impacts of a single crop may vary due to differences in yields related to variable weather conditions (Notarnicola et al., 2017). Secondary data were obtained from the Ecoinvent 3.5 database from the SimaPro 9.0 library with the cut-off attributional model.

In the case of melons and watermelons, the farm production of both species was analyzed together since they belong to the same botanical family (*Cucurbitaceae*) and have the exact agronomic requirements. For example, both crops require warm climates, well-drained and light soils, and a slightly acidic to neutral pH. They prefer drip irrigation to maintain adequate moisture and demand nutrients such as nitrogen, phosphorus, and potassium, often applied through fertigation. Additionally, they face similar pests and diseases, rely on pollinators like bees, and have short growing cycles of approximately 70 to 90 days (Pitrat, 2008; Wehner, 2008). These similarities allow farmers to apply common management practices and techniques, optimizing resources in

Table 2
Global inventory for 1 kg of melon/watermelon produced in Costa Rica and consumed in the EU.

Stage	Materials	Unit	Value
Farm Production	**Inputs**		
	Natural resources		
	Water	m^3	0.04
	Land use	m^2/year	0.29
	Energy and fuels		
	Diesel	kg	9.53E-03
	Gasoline	kg	2.94E-05
	Electric power (Costa Rica)	kWh	9.20E-03
	Raw materials		
	Bedding plastic (LDPE)	kg	8.43E-03
	Agribon (HDPE)	kg	2.78E-04
	Fertilizers		
	N, ammonium nitrate	kg	2.67E-03
	P_2O_5	kg	2.22E-03
	K_2O	kg	4.78E-03
	Pesticides and herbicides		
	Spirotetramat	kg	6.11E-06
	Spinosad	kg	7.88E-07
	Emamectin benzoato	kg	1.85E-06
	Fungicides		
	Clorotalonil	kg	4.16E-05
	Propamocarb hydrochloride (62.5 %)	kg	6.26E-06
	Mancozeb 80 %	kg	2.99E-05
	Total pesticides [i.a.]	kg	8.66E-05
	Outputs		
	Melon	kg	1.00E+00
	Atmospheric emissions		
	NH_3	kg	4.17E-04
	NO_2	kg	9.00E-05
	N_2O	kg	9.65E-05
	CO_2	kg	3.44E-02
	CH_4	kg	2.80E-05
	CH_4 Biogenic	kg	5.46E-06
	Water (evapotranspiration)	m^3	4.56E-02
	Spirotetramat	kg	5.50E-07
	Spinosad	kg	7.09E-08
	Emamectin benzoate	kg	1.67E-07
	Clorotalonil	kg	3.74E-06
	Propamocarb HCl	kg	5.63E-07
	Mancozeb	kg	2.70E-06
	Aquatic emissions		
	N	kg	3.47E-04
	NO_3^-	kg	8.81E-04
	P	kg	6.66E-05
	Spirotetramat	kg	6.11E-08
	Spinosad	kg	7.88E-09
	Emamectin benzoate	kg	1.85E-08
	Clorotalonil	kg	4.16E-07
	Propamocarb HCl	kg	6.26E-08
	Mancozeb	kg	2.99E-07
	Terrestrial emissions		
	Spirotetramat	kg	5.50E-06
	Spinosad	kg	7.09E-07
	Emamectin benzoate	kg	1.67E-06
	Clorotalonil	kg	3.74E-05
	Propamocarb HCl	kg	5.63E-06
	Mancozeb	kg	2.70E-05
Post-harvest treatment and packaging	**Inputs**		
	Natural resources		
	Melon/Watermelon	kg	1.0
	Water	m^3	5.57E-04
	Energy and fuels		
	Gasoline	kg	2.61E-04
	Electric power (Costa Rica)	kWh	1.21E-02
	Liquefied petroleum gas	kg	2.40E-05
	Raw materials		
	Corrugated cardboard	kg	3.89E-02
	Post-harvest products		
	NaClO	kg	2.49E-05
	Outputs		
	Packed melon/watermelon	kg	1.00389
	Atmospheric emissions		
	N_2O	kg	7.03E-08
	CO_2	kg	9.23E-04
	CH_4	kg	2.35E-06
	Aquatic emissions		
	Chlorine	kg	2.49E-05
	Wastewater	m^3	5.15E-04
Distribution and retail	**Inputs**		
	Electric power (Costa Rica)	kWh	0.020
	Transport, freight, sea, transoceanic ship with reefer, cooling	t.km	9.17
	Packed melon/watermelon	kg	1.0389
	Electricity, high voltage, production mix | electricity, high voltage | Cut-off, S – NL	kWh	0.02
	market group for electricity, low voltage | electricity, low voltage | Cut-off, S – RER	kWh	0.02
	Transport, freight, lorry > 32 t, EURO 4	t.km	0.08
	Ethylene	kg	3.70E-05
	Freon gas (R404a)	kg	1.10E-04
	Outputs		
	Melon/watermelon	kg	1
	Corrugated cardboard	kg	3.89E-02
	Ethylene	kg	3.70E-05
	Ethane 1,1-difluoro-, HFC-152[a]	kg	1.10E-04
Household consumption	**Inputs**		
	Melon/watermelon	kg	1
	Transportation in a light commercial vehicle	km	0.185
	Plastic bag LDPE	kg	0.0025
	Water	m^3	8.80E-04
	Outputs		
	Solid residues	kg	0.42
	Water	m^3	8.80E-04

their production.

Inventory data is summarized in Tables 1 and Table 2, specified for each stage considered in this study for 1 kg of banana and 1 kg of melon/watermelon produced in Costa Rica and consumed in the EU.

In order to identify the environmental aspects associated with electricity consumed along the supply chain of the studied fruits in Costa Rica, the Ecoinvent v.3.5 database was used. While Costa Rica's electricity data is not available in this database, it was developed using national statistics for the year of study: hydro (69.2 %), geothermic (13.4 %), wind (15.8 %), cogeneration (0.6 %), natural gas (0.9 %), and solar (0.1 %) (ICE, 2019).

In the distribution and retail stage, data were obtained from other LCA studies of fruit production in Costa Rica (Luske, 2010; Svanes, 2012; Svanes and Aronsson, 2013) and fruit import studies in Europe (Frankowska et al., 2019; Stoessel et al., 2012). Therefore, it is worth mentioning that data from these stages, such as electricity consumption, local transport in Europe, and fugitive emissions of refrigerants, refer to studies that have already been carried out and may present a source of variability in the results.

In addition, N_2O emissions were modeled according to the guide for the environmental footprint of coffee (Gmünder et al., 2020) with a value of 0.2 kg of N_2O/kg of nitrogen fertilizer. Nitrogen and phosphorus emissions to water significantly influence the aquatic and marine eutrophication categories. Thus, the potential impacts were analyzed following the Franke et al. (2013) recommendations when there are no site-specific emission models. This means default global average leaching-runoff fractions that can be used if no local information is available. A sensitivity analysis was performed to determine the influence of these parameters on the model.

Moreover, fruit losses along the value chain were not considered. These losses happen at warehouses, supermarkets, and the consumer's home.

Finally, generic emission models according to Franke et al. (2013) were used to apply fertilizers and pesticides (using "RoW Market" and "Pesticide, unspecified" datasets from Ecoinvent, respectively). These models do not consider the climatic or edaphic conditions that should be site-specific. In the agricultural sector, site-dependent and environmental aspects acquire particular relevance, and nowadays, there is no consensus on a globally applicable model for calculating soil and water emissions, which are more dependent on soil conditions (Notarnicola et al., 2017).

2.3.1. Farm production

The production process of bananas (perennial plantation) operates year-round, with no need for replanting for up to 30 years. Manual fertilization includes ammonium nitrate, potassium, phosphorus and organic fertilizers (poultry manure and animal waste). Ammonium nitrate provides nitrogen in both ammonium (NH_4^+) and nitrate (NO_3^-) forms, directly influencing the nitrogen cycle by facilitating plant uptake (George, 2014) and organic fertilizers contribute organic nitrogen, which is mineralized by soil microbes into ammonium, then nitrified into nitrate, ensuring continuous nitrogen availability (Lazcano et al., 2021). For fumigation, the fungicide Mancozeb is applied via aerial spraying, consuming Jet-Fuel A-1. The fruit is protected with recyclable plastic bags and reusable polyethylene foam. Harvesting and transportation to the packing plant are conducted manually using a banana cableway trolley system.

For melons and watermelons, a conventional farming was considered, involving a series of key agricultural activities. First, soil amendments are made to optimize growing conditions, and nurseries are established with an adequate supply of raw materials, including fertilizers, pesticides, and protective plastics. Irrigation is done through a drip system, an efficient method that, together with fertigation, ensures controlled application of water and nutrients. This process requires a considerable amount of energy and fuel consumption, both for irrigation and for applying inputs. The harvesting of melons and watermelons is done manually, which involves labor in the field. Additionally, diesel is used to transport the fruit from the production site to the packing plant, thus closing the production cycle in the field before entering the commercialization phase.

All agricultural activities are considered, from soil amendments, seedlings, and supply of raw materials (organic and inorganic fertilizers, pesticides, and protective plastics) to the farms and use of fuels. Following the Intergovernmental Panel on Climate Change (IPCC) criteria, emissions from land-use transformation were not considered since the cultivated areas have been producing bananas and melons/watermelons for >20 years (IPCC, 2003).

Emissions from applying fertilizers (ammonium nitrate, potassium, and phosphorus) were estimated per the recommendations for life cycle inventories in the agricultural sector (Nemecek et al., 2019). Due to the intensity of fertilizer application, the soil acidifies, and calcium carbonate and dolomitic lime are applied to control pH.

In the case of pesticides, it was estimated as follows: for every kilogram of active ingredient, 90 % stays in the soil, 9 % volatilizes, and 1 % runs off into the water (Gmünder et al., 2020). Energy and fuel consumption for applying pesticides were considered (aerial fumigation in the banana case). The harvest is manual, so no energy source is required in this step. To transport the fruit to the packing plant, bananas are handled differently than melons and watermelons. Once banana bunches are harvested, they are lifted onto an overhead conveyor system and then slid onto a cableway trolley, which is pulled by a person into the packing plant, requiring no energy for this step. In contrast, for melons and watermelons, diesel consumption for transporting the fruit from the field to the packing plant is taken into account.

2.3.2. Post-harvest treatment and packaging

The post-harvest fruit handling and packing installations are located at the farm.

All activities are included since the fresh fruit arrives at the packing plant, including water for washing, post-harvest products such as fungicides, electricity, fuels, and packaging materials. The infrastructure for the packing plant is not considered. The wastewater treatment plant, where effluents are treated, was not considered either.

2.3.3. Distribution and retail

The distribution starts with the local transportation of the packed fruit in refrigerated trucks from the moment it leaves the packing plant until it reaches the outbound port in Limón, Costa Rica (100 km). Afterward, international transport was considered, including the activities of the outbound port, energy consumed in the port, and fuels for marine transport from Costa Rica to The Netherlands (9175 km). The ship was assumed to carry refrigerated containers. Finally, for the regional distribution in the EU, all storage activities, transport to local supermarkets (78 km), and refrigeration in Europe were considered.

2.3.4. Household consumption

The consumption stage includes the activities of an average consumer in Europe, which means using a passenger car from home to the supermarket and vice versa (0.185 km), using a 2.5 g plastic bag and water to wash the fruit. The energy required for refrigeration is not included as it is assumed that the fruit is consumed fresh.

2.3.5. End-of-life

In this stage, an average municipal landfill in Europe was considered in the waste management process. In addition, it was assumed that the plastic bag used for transportation and the non-edible portion of the fruit goes into the garbage.

2.4. Impact assessment

The life cycle impact assessment was based on the local situation and used to evaluate the quantity and significance of potential environmental impacts from a defined system throughout its entire life cycle (ISO, 2006a, 2006b).

The fruit production process was modeled in SimaPro 9.0 (PRé Consultants, Amersfoort, the Netherlands). ReCiPe midpoint (hierarchist version) was used for the impact assessment, where 11 impact categories were evaluated, including the categories required in the product category rules (PCR) for fruits and nuts (The International EPD® System, 2019): global warming (GW), stratospheric ozone depletion (SOD), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME), terrestrial ecotoxicity (TEx), freshwater ecotoxicity (FEx), marine ecotoxicity (MEx), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNT) and land use (LU).

2.5. Sensitivity analysis

A sensitivity analysis was developed considering different end-of-life processes in order to study how different scenarios could influence environmental profiles.

3. Results and discussion

In this section, life cycle impact assessment is described and discussed. There is one section for each studied crop with their respective environmental profiles, carbon footprint, and sensitivity analysis.

3.1. Banana

The LCA results of the impact categories selected in this study, for the

Table 3
Potential environmental impacts derived from the cradle to grave LCA of 1 kg of banana.

Impact category	Unit/UF	Total
Global warming	kg CO_2 eq	8.05E-01
Stratospheric ozone depletion	kg CFC11 eq	4.15E-06
Terrestrial acidification	kg SO2 eq	6.04E-03
Freshwater eutrophication	kg P eq	1.63E-03
Marine eutrophication	kg N eq	5.94E-04
Terrestrial ecotoxicity	kg 1,4-DCB	9.79E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.74E-01
Marine ecotoxicity	kg 1,4-DCB	1.95E-01
Human carcinogenic toxicity	kg 1,4-DCB	3.13E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	2.94E+00
Land use	m^2a crop eq	1.61E-01

production and consumption of 1 kg of banana are shown in Table 3.

Fig. 2 shows the contribution of each stage involved in banana production towards each impact category. The stages that affect the most are farm production, distribution and retail (international transport), and the end-of-life stage. As a consequence of the production and flow of nutrients and pesticides from the field, the agricultural stage is often found to be the major contributor to many impact categories (Dijkman et al., 2018).

In this case, the farm production stage contributes with 90 % of the impacts of land use, stratospheric ozone depletion, and freshwater eutrophication. It also contributes with 80 % of the impacts of marine eutrophication and terrestrial ecotoxicity. On the other hand, the international shipping stage contributes with >20 % of the impacts of global warming and human carcinogenic toxicity and >40 % to the potential impacts of the terrestrial acidification category. Finally, waste management (end-of-life stage) contributes with >80 % of the potential impacts of freshwater and marine ecotoxicity and human non-carcinogenic toxicity. This stage also contributes with 36 % of global warming and 48 % of human carcinogenic toxicity.

Results of the impact assessment show that, in the case of banana cultivation in Costa Rica, field activities are contributing significantly to the studied impact categories. Here, a considerable number of emissions are produced by applying fertilizers (N_2O, NH_3, NO_2, P, N, and NO_3) and pesticides (mancozeb) that reach the different environmental compartments. In fact, mancozeb emissions generate the majority of terrestrial ecotoxicity impacts. Similar results has already been documented for banana crops in Costa Rica (Mendez et al., 2018).

By observing the contribution of the system processes towards the life cycle impacts, it can be identified that the supply of nitrogen fertilizers and pesticides also has a significant influence.

Nitrogen fertilizer manufacturing contributes with 40 % of stratospheric ozone depletion impacts.

Considering that bananas are consumed overseas, international refrigerated transportation is a stage that highly contributes towards three impact categories, as stated in the study of Craig et al. (2009). In fact, the distribution phase is crucial in fresh products life cycles such as fruits and vegetables, where this stage requires refrigerated transport and storage, representing a significant contribution to the total impacts (Dijkman et al., 2018). Refrigerated ships use fossil bunker and fuel oil as fuel, so their CO_2, NOx, and SOx emissions are highly polluting and influence the categories of acidification and ozone formation. These facts highlight the importance of considering the export destination, the distance, and the means of transport to take the fruit to its final destination.

In this study, waste management is relatively high due to the high amount of the non-edible part of the fruit (38.6 % of the total fruit (Frankowska et al., 2019; Roibás et al., 2016; Svanes and Aronsson, 2013)). It has a significant influence on the toxicity impact categories. One of the reasons is that the ReCiPe 2016 (H) method gives a high weight to the emission of heavy metals such as copper, chromium, lead, and zinc that occur in this stage. In addition, the Regional European dataset called "Market for treatment of Municipal Solid Waste, Landfill" from Ecoinvent dabase was used to represent the waste treatment stage of the fruit.

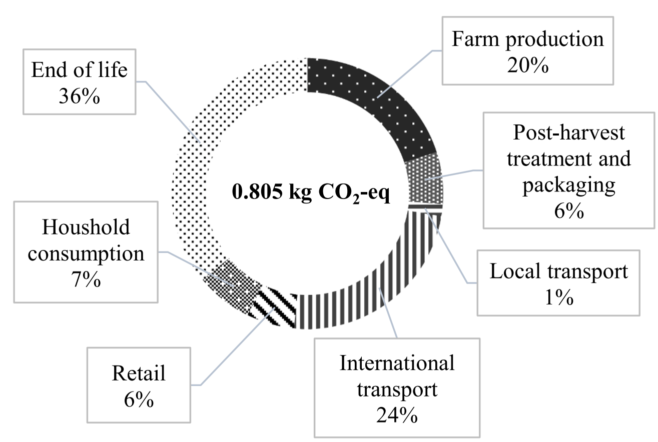

Fig. 3. Carbon footprint of 1 Kg of banana produced in Costa Rica and consumed in Europe.

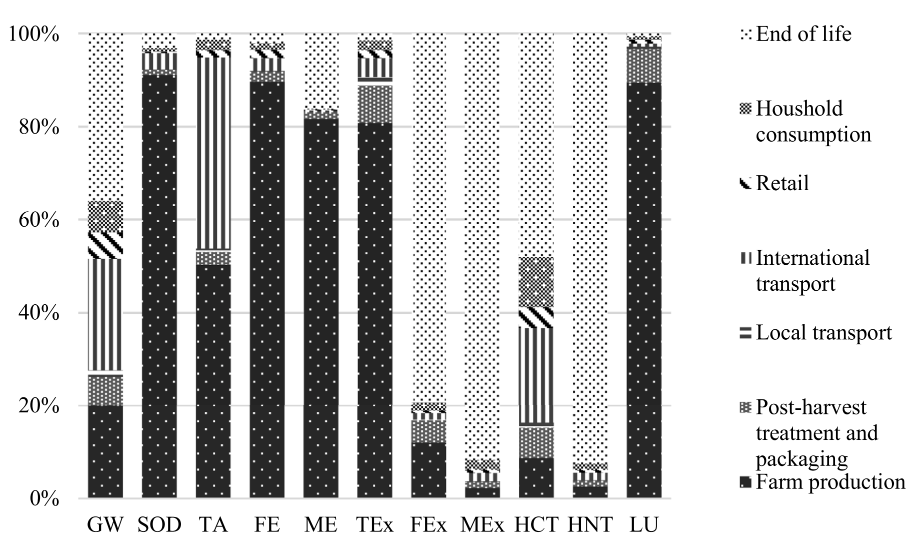

Fig. 2. Contribution of each stage involved in the banana life cycle.

Table 4
Comparative analysis of carbon footprint results for banana crops.

Source	Country of production	Place of consumption	Approach	Carbon footprint	Hotspot detected
This study	Costa Rica	The Netherlands	Cradle-to-grave	0.805 kg CO_2-eq/kg	Waste management and overseas transport
Luske (2010)	Costa Rica	Germany	Cradle-to-gate	1.24 kg CO_2-eq/kg	Use of fertilizers and overseas transport
Stoessel et al. (2012)	Peru	Switzerland	Cradle-to-shelf	0.019 Pt	–
	Ecuador	Switzerland	Cradle-to-shelf	0.019 Pt	–
	Costa Rica	Switzerland	Cradle-to-shelf	0.017 Pt	–
	Colombia	Switzerland	Cradle-to-shelf	0.015 Pt	–
Kilian et al., (2012)	Costa Rica	Europe	Cradle-to-grave	1.087 kg CO_2-eq/kg	Maritime Shipping
Svanes and Aronsson (2013)	Costa Rica	Norway	Cradle-to-retail	1.37 kg CO_2-eq/kg	Overseas transport, primary production and waste management
Iriarte et al. (2014)	Ecuador	Germany	Cradle-to-gate	0.45- 1.04 kg CO_2-eq/kg	Farm production and overseas transport
Roibás et al. (2016)	Ecuador	Spain	Cradle-to-grave	1.28 kg CO_2-eq/kg	Farm production
Frankowska et al. (2019)	Colombia, Ecuador and Costa Rica	UK	Cradle-to-grave	1.3 kg CO_2-eq/kg	Transport
Veliz et al. (2022)	Ecuador	The Netherlands	Cradle-to-gate	0.615 kg CO_2-eq/kg	Farm production

3.1.1. *Carbon footprint*

The carbon footprint for the banana supply chain was estimated at 0.805 kg CO_2-eq/kg of bananas consumed in Europe. The results indicate that bananas had a carbon footprint (CF) similar to other tropical fruits (Stoessel et al., 2012) and that the contribution from the farm production stage was low, as can be seen in Fig. 3. This is similar to that estimated by other researchers (Stoessel et al. 2012; Iriarte et al. 2014; Veliz et al. 2022), but it is lower than the results of other studies which vary between 1.0 - 1.8 kg CO_2-eq/kg of banana (Frankowska et al., 2019; Kilian et al., 2012; Luske, 2010; Roibás et al., 2016; Svanes and Aronsson, 2013), summarized in Table 4.

The variation arises from factors such as accounting for fruit losses throughout the supply chain, emissions related to organic waste disposal, the diversity in transportation methods, and disparities in the edible portion of the fruit.

When the carbon footprint is analyzed considering the percentage of contribution, it can be noted that the results are similar to what other studies reported (Luske, 2010; Stoessel et al., 2012; Svanes and Aronsson, 2013), where the agricultural stage and packaging contribute around 25 % of total emissions. The stages that are the significant contributors are end-of-life or waste management, international transport, and farm production. Therefore, more attention is needed in these stages to improve the environmental performance of this product regarding its CF.

3.1.2. *Sensitivity analysis*

This section outlines the sensitivity analysis aimed at assessing how the results may be affected by alterations in specific inventory parameters.

3.1.2.1. Effect of the waste management process in Ecoinvent 3.5 cut-off. Due to the very high contribution (> 90 %) of waste management (end-of-life) in the toxicity impact categories, different processes of the landfill from the Ecoinvent 3.5 database were compared as follows:

- Market group for municipal solid waste | RER Market Group
- Treatment of municipal solid waste, sanitary landfill | CH Sanitary landfill

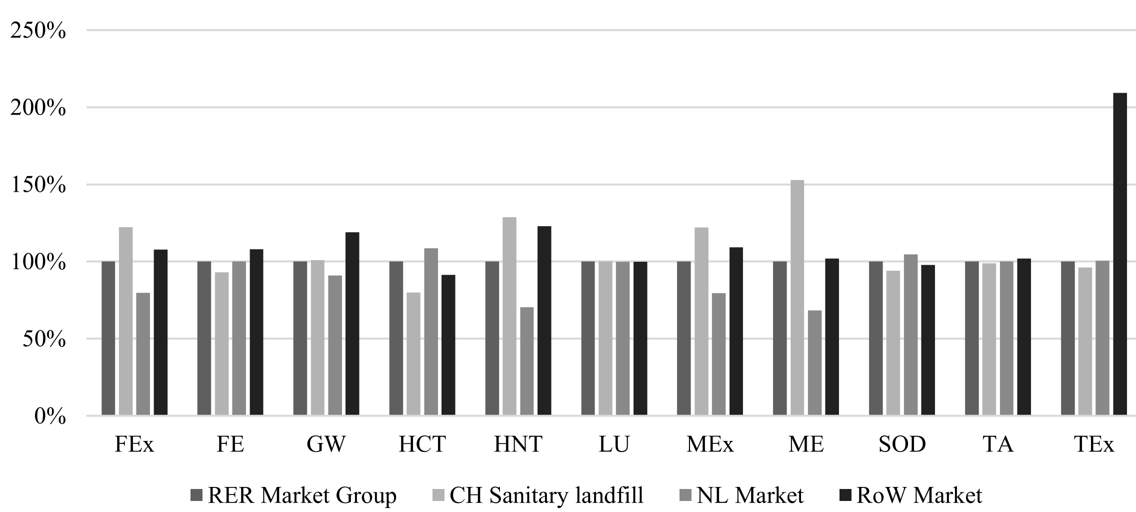

Fig. 4. Sensitivity analysis to landfill processes from the Ecoinvent database 3.5 for banana supply chain.

Table 5
Potential environmental impacts derived from the cradle to grave LCA of 1 kg of melon/watermelon.

Impact category	Unit/UF	Total
Global warming	kg CO_2 eq	8.22E-01
Stratospheric ozone depletion	kg CFC11 eq	2.05E-06
Terrestrial acidification	kg SO_2 eq	4.20E-03
Freshwater eutrophication	kg P eq	1.12E-03
Marine eutrophication	kg N eq	3.47E-04
Terrestrial ecotoxicity	kg 1,4-DCB	2.98E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.65E-01
Marine ecotoxicity	kg 1,4-DCB	2.18E-01
Human carcinogenic toxicity	kg 1,4-DCB	3.29E-02
Human non-carcinogenic toxicity	kg 1,4-DCB	3.27E+00
Land use	m^2a crop eq	3.18E-01

- Market for municipal solid waste | NL Market
- Market for municipal solid waste | RoW Market

The selected scenario for the study was “Market group for municipal solid waste” and Fig. 4 shows the change in the results relative to the original scenario (RER market = 1). Results demonstrate that the impact categories that present variation greater than 20 % are those of toxicity and marine eutrophication. These variations are directly related to the weight that ReCiPe allocates to heavy metal emissions. In the other impact categories, the results do not vary >20 %, which is why it is concluded that the selected process is suitable to represent an average municipal sanitary landfill in Europe.

3.2. Melon and watermelon

The LCA results of the impact categories selected in this study, for the production and consumption of 1 kg of melon/watermelon, are shown in Table 5.

Fig. 5 shows the contribution of each stage of the melon and watermelon life cycle towards each impact category. The stages that contribute the most or hotspots are end-of-life (waste management), international transport, and agricultural farming activities, as well as in the banana case.

The farm production stage contributes 80–90 % of the potential impacts of land use and stratospheric ozone depletion. In addition, it contributes between 40 and 60 % with the impacts of freshwater and marine eutrophication. On the other hand, the international shipping stage contributes with 59 % to terrestrial acidification and around 20 % to the categories of climate change and human carcinogenic toxicity. Finally, the waste management stage (end-of-life) contributes with >90 % of the potential impacts of freshwater ecotoxicity, human non-carcinogenic toxicity, and marine ecotoxicity. It also contributes between 30 and 50 % to climate change, human carcinogenic toxicity, and marine eutrophication.

Results obtained in this study are consistent with findings from other studies of fruits imported to Europe (Frankowska et al., 2019; Iriarte et al., 2014) or to the United States (Craig et al., 2009; Ingwersen, 2012).

The potential impacts related to field activities are related to nitrous oxide (N_2O) emissions into the air and nitrogen and phosphorus into the water, which significantly influence the aquatic and marine eutrophication categories. International refrigerated ship transportation contributes significantly to all impact categories. As mentioned in the banana case, these ships use fossil fuels such as bunker and fuel oil, so their CO_2, NOx, and SOx emissions are highly polluting and influence the impact categories of global warming and terrestrial acidification.

In this study, the solid waste management stage has a relatively high contribution to some of the impact categories studied due to the high percentage of non-edible percentage of melons and watermelons (42 % of the total fruit (Capossio et al., 2022; Frankowska et al., 2019; Valle-Vargas et al., 2020)), which goes to waste and need to be treated at the end-of-life.

3.2.1. Carbon footprint

Fig. 6 shows the carbon footprint for the supply chain of melon and watermelon produced in Costa Rica. It was estimated at 0.822 kg of CO_2-eq/kg of melon or watermelon consumed in Europe, which is very close to the reported data: 0.71 - 0.9 kg of CO_2-eq/kg of melon (Azizpanah

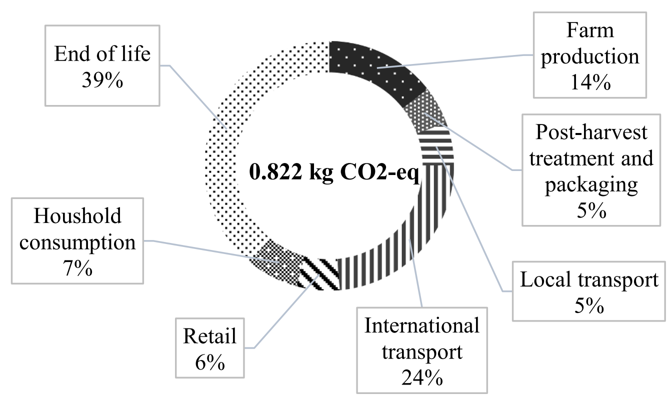

Fig. 6. Carbon footprint of 1 Kg of melon and watermelon produced in Costa Rica and consumed in Europe.

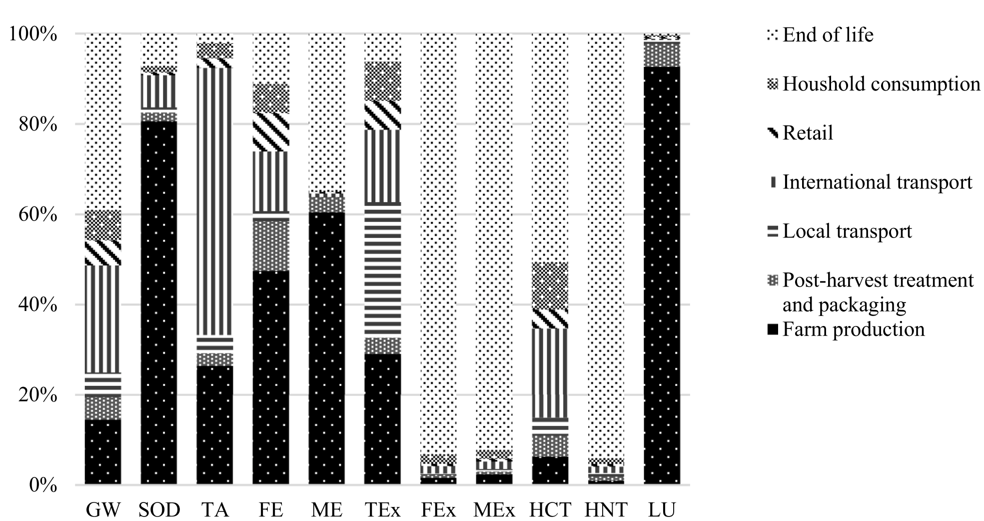

Fig. 5. Contribution of each stage involved in melon/watermelon life cycle.

Table 6
Comparative analysis of carbon footprint results for melon/watermelon crops.

Source	Country of production	Place of consumption	Approach	Carbon footprint	Hotspot detected
This study	Costa Rica	The Netherlands	Cradle-to-grave	0.822 kg CO_2-eq/kg	Waste management and overseas transport
De Figueirêdo et al., 2013	Brazil	The Netherlands	Cradle-to-gate	0.710 kg CO_2-eq/kg	Farm production
Frankowska et al. (2019)	–	UK	Cradle-to-grave	0.9 kg CO_2-eq/kg	Transportation
Barros et al. (2019)	Brazil	The Nethrelands	Cradle-to-grave	0.754 kg CO_2-eq/kg	Farm production
Azizpanah et al. (2023)	Brazil	–	Cradle-to-gate	0.155 kg CO_2-eq/kg	Machinery

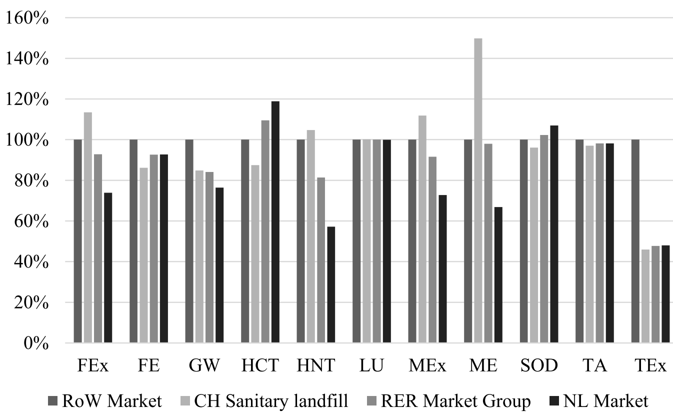

Fig. 7. Sensitivity analysis to landfill processes from the Ecoinvent database 3.5 for melon and watermelon supply chain.

et al., 2023; Barros et al., 2019; De Figueirêdo et al., 2013; Frankowska et al., 2019), summarized in Table 6. Upon arrival at the outbound port in Costa Rica, the potential impact on climate change is 0.22 kg of CO_2-eq/kg, which represents 24 % of the total emissions in the supply chain. International transport, which represents 24 %, and waste management, which represents 39 % of the total impacts of climate change, are the two stages of the supply chain that need more attention to improve the carbon footprint of these fruits.

3.2.2. Sensitivity analysis

3.2.2.1. Effect of the waste management process in Ecoinvent 3.5 cut-off. Due to the very high contribution (> 90 %) of waste management (end-of-life) in the toxicity impact categories, different process of landfill available in Ecoinvent 3.5 database were compared as stated in Section 3.1.2.1.

Fig. 7 shows the differences between the original scenario “market group for municipal solid waste” (RER Market = 1) and the other three selected. The impact categories that present a variation range greater than 20 % are those of toxicity and marine eutrophication. These variations are directly related to the weight that ReCiPe allocates to heavy metal emissions. In the other impact categories, results do not vary >20 %, which is why it is concluded that the selected process is adequate to represent an average municipal sanitary landfill in Europe.

4. Conclusions

Using LCA to analyze a value chain can give access to quantitative indicators that can be used to improve environmental sustainability and address the global demand for more sustainable consumption and production. Considering that bananas, melons, and watermelons are fruits of worldwide interest due to their high consumption, it is concluded that these crops should receive more attention for their environmental performance than the little that they have received so far. This lack of attention can be attributed to the fact that the production of these fruits is focused on tropical and developing countries. As can be seen in the results, most of the impacts in the different categories are attributed to field activities and end-of-life. For field activities, adopting more sustainable agricultural practices such as precision farming, optimized water usage, and reduced pesticide application can substantially lower the environmental impact. Additionally, innovation in production systems, such as integrating renewable energy sources or implementing agroecological practices, could contribute to reducing the carbon footprint. Regarding the end of life, developing better waste management strategies to handle the large proportion of non-edible biomass, such as valorizing organic waste through composting or bioenergy generation, could mitigate the toxic impacts associated with disposal. Thus, improving the environmental sustainability of these crops is in the hands of producers and entities in charge of waste management. With international organizations’ support, local governments could promote these improvements, basing their decisions on scientific information such as life cycle assessment results. These improvements could position Costa Rica as a global leader in the sustainable production of tropical fruits, setting a precedent for other tropical and developing countries aiming to meet international sustainability goals.

CRediT authorship contribution statement

Nydia Suppen-Reynaga: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Ana Belén Guerrero:** Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation. **Elena Rosa Dominguez:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation. **Edgar Sacayón:** Methodology, Investigation, Formal analysis, Conceptualization. **Andrea Solano:** Writing – review & editing, Validation, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Nydia Suppen-Reynaga reports financial support was provided by The World Bank Group. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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