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Life cycle assessment of citrus tree nurseries in Uruguay: Are their environmental impacts relevant?

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ABSTRACT

Perennial fruit production at the commercial scale, such as citrus fruits, begins with seedling production in a nursery. This stage lasts several months and involves different phases and the use of substrates and infrastructure. As the seedling does not produce fruit but does consume inputs, studying the environmental impacts associated with this stage becomes relevant, especially to understand its contribution to the total impact of the crop cycle. Despite the global relevance of fruit tree seedlings production, LCA studies in the literature focus on horticultural crop nurseries, and those on perennial tree nurseries do not consider both substrate and structures in the analysis, which is key for this type of crop since the main production system is soilless production in greenhouses. Thus, the main goal of this study is to quantify the environmental impacts related to the production of citrus fruit tree seedlings using LCA, analyse the main production system applied nowadays, and study its relevance with respect to the crop cycle. To this end, a certified Uruguayan citrus nursery was analysed, from which primary data was obtained. As well, methodological issues concerning water consumption and modelling emissions from input applications in soilless greenhouse systems are tackled. Results show that the main hotspots of the nursery stage are infrastructure production and peat transportation, which highlights the relevance of their inclusion when modelling the system. Extending the lifespan of the galvanised steel structures and decreasing substrate transport distances are shown to be effective measures to reduce environmental impacts. The contribution of the nursery stage to the citrus production cycle is negligible for almost all the impact categories assessed except cancer human toxicity, as it accounts for 0–3.6% of the impacts depending on the impact category. Great differences (from 10 to 400 times higher results on average) are observed when comparing the results with those from commercial databases, as they consider open-field nurseries where seedlings are grown in the soil. The need to develop harmonised methods to model water consumption and fertiliser and pesticide emissions for soilless crops in greenhouses arises. The present study presents a complete quantification of the environmental impacts of the main production system of citrus fruit tree seedlings and provides scientific and quantitative evidence of its contribution to the production cycle, helping decision-makers understand where efforts should be focused to achieve a more sustainable fruticulture.

1. Introduction

Whether its destination is export, industry, or domestic consumption, perennial fruit production in general, and in particular that of citrus, necessarily entails a nursery stage where the plant does not bear fruit but consumes inputs. Producing certified seedlings is a critical component of good agricultural practices programs for developing healthy plantations (Harwanto et al., 2023). Certification programs worldwide demand the growth of fruit tree seedlings in containers with substrates in greenhouses (Furlani et al., 2009; Natale et al., 2018; Vashisth et al., 2020), as seedlings produced inside protected structures grow disease-free trees (Davies and Zalman, 2008) and the production in containers facilitates the development of a vigorous root system that results in more robust plants (Castle, 1987). Citrus fruit production has special importance worldwide, with 143,756 thousand tonnes of citrus fruits produced in 2019 (FAO, 2021). In Uruguay, it is the most relevant fruit crop in terms

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of tonnes and area (MGAP, 2022a). Between 2017 and 2019, an average of 541,916 citrus seedlings, mainly lemons and mandarins, were produced annually in the country (Gabriel Fontán 2023, personal communication). Nurseries are concentrated in the south (62% of total nurseries), mainly to minimise the spread of diseases, as opposed to the concentration of citrus orchards, mostly located in the north (91%) (MGAP, 2022b). In line with certification programs worldwide, the National Seed Institute (INASE) strictly controls the production of seedlings based on a specific production standard (INASE, 2021), being certification mandatory at the national level; therefore, all nurseries must be inscribed in the General Seed Registry (INASE, 2023) and comply with the standard.

Life cycle assessment (LCA) is a valuable tool to quantify the environmental impacts associated with this stage, as it considers the whole production system (Casson et al., 2023) and has been successfully applied to agricultural production (Basavalingaiah et al., 2022; Ding et al., 2023; Ghani et al., 2023). Previous studies on the environmental impacts of perennial crops highlight the importance of considering the impacts associated with this stage due to the long time from sowing until the plant is ready to be transplanted in the orchard and the intensive use of inputs that it can entail (Bessou et al., 2013; Cerutti et al., 2014). Nevertheless, only a few citrus studies consider this stage, and those that do it, do not provide enough data to understand how the modelling was performed (Bessou et al., 2016) or use secondary data from commercial inventory databases (Martin-Gorriz et al., 2020). Furthermore, nursery processes available in inventory databases correspond to open-field nurseries where seedlings are grown in the soil, which is different from the main production system of seedlings for perennial fruit trees. According to Perrin et al. (2014), the nursery stage should be included unless it can be demonstrated that its contribution to the impacts is negligible. Along these lines, developing studies that quantify this stage's environmental impacts using primary data with a detailed inventory description and comparing them with those from the remaining crop cycle stages becomes relevant (Cabot et al., 2022).

Published LCAs for food production in nurseries are centred on horticultural products, especially tomatoes in the Mediterranean region (Boulard et al., 2011; Torrellas et al., 2012a), Hungary and the Netherlands (Torrellas et al., 2012b), and Colombia (Bojacá et al., 2014). Studies have also been found for peppers, melons, zucchini, and green beans (Cellura et al., 2012; Romero-Gámez et al., 2012). Although these studies also involve production in greenhouses, crops are primarily grown in the soil, and the inputs applied and the crop cycle lengths differ from those of citrus. Regarding perennial trees' nurseries, studies have been carried out on cashews in Brazil (Brito De Figueirêdo et al., 2016), walnuts in Italy (Cambria and Pierangeli, 2011) and apples in France (Alaphilippe et al., 2016), which present significative differences with those of citrus. Among them, the seedling growth period differs (from 3 months for cashews to 24 months for apples and walnuts), and none of the three studies considers both substrate and structures in the analysis. Considering that these are found as hotspots in other studies on nurseries (Romero-Gámez et al., 2012; Torrellas et al., 2012a) and that differences in the crop cycle lengths can involve significant differences in the results, the development of the present study gains relevance.

As to the methodological issues, the modelling of water consumption by the crop and emissions from the application of fertilisers and pesticides in greenhouses, especially in soilless crops, represent a challenge in LCA application, as there are no consensus models to follow (Antón et al., 2019). In the reviewed studies, the authors assume the worst-case scenario where the crop consumes all the irrigation water, which can lead to an overestimation of water consumption. Likewise, N_2O emissions, which are relevant in soilless crops (Pitton et al., 2021), are calculated using emission factors (EFs) for cultivation in soil, which differ from those for cultivation in substrates. To estimate NO_3^- leaching, Bojacá et al. (2014) and Alaphilippe et al. (2016) perform an N balance. However, the former considers the same N uptake for the entire growing season, and the latter considers annual values. In addition, the authors do not model pesticide emissions except for Bojacá et al. (2014), who apply the proposal of Antón et al. (2004), where emissions from cultivation in soil and substrates are not differentiated.

To fill the gaps detected in the LCA literature on fruit tree seedlings and to contribute to a more accurate evaluation of citrus production in Uruguay, this study aims to quantify the environmental impacts of the production of citrus fruit tree seedlings using primary data from a certified citrus nursery, representative of soilless seedlings production in greenhouses, and to address the methodological issues mentioned above. In this way, we seek to set a benchmark for citrus fruit tree nurseries and analyse the hotspots detected while suggesting alternatives to minimise their impact. In addition, to understand the significance of the environmental impacts of the nursery stage in the citrus fruit life cycle, an estimation of its contribution to the overall process is performed.

2. Materials and methods

This study follows the LCA methodology based on ISO standards (ISO, 2006a, 2006b; ISO, 2017; ISO, 2020a; ISO, 2020b) using GaBi software (Sphera Solutions GmbH, Leinfelden-Echterdingen, Germany). PCRs for fruits (EPD, 2019) state that if the nursery stage is under the organisation's direct control, operations providing seedlings should be modelled using primary data. However, they do not provide specific guidelines for this modelling.

2.1. System description

The studied citrus nursery is located in Rodríguez, San José Department, south of Uruguay. It comprises 31 greenhouses of approximately 450 m^2 each. Two of them are used for growing seedlings in seedbeds, one has the grafting material, another one has the mother plants, which are the company's germplasm bank with a collection of plants from 15 to 20 years old, and the remaining 27 greenhouses are used for growing seedlings in pots. The nursery can be considered representative for several reasons; firstly, the seedlings produced are certified and comply with the specific INASE (2021) standard, which is in agreement with certification standards worldwide. Secondly, because the species produced are lemon and mandarin, the most grown in Uruguayan citrus nurseries (Gabriel Fontán 2023, personal communication). Lastly, the proposed production scheme allows for 100,000 annual seedlings to be produced, representing 19% of the citrus seedlings in the country and 21% of the specific production of lemons and mandarins.

The cultivation process in the nursery lasts up to 28–32 months and begins with the rootstocks sowing in seedbeds, usually during the first winter months of the 1st year. The seedlings develop throughout the winter and spring of that year, and in the first months of summer, which correspond to the end of the 1st year and the beginning of the 2nd, young seedlings are transplanted into pots, while in autumn of the 2nd year, the seedlings are grafted with the corresponding citrus variety ('autumn graft'). Occasionally, in that year, the so-called 'spring graft' is carried out for seedlings that were not grafted before. In the spring of the 3rd year, the seedlings are ready to be transplanted in the orchard. In some cases, ready-to-go seedlings grafted in autumn can be transplanted in the orchard by the early summer of the 2nd year (usually lemon seedlings, as they tend to grow faster). These seedlings typically reach less than 30% of the total seedlings in the greenhouse.

The rootstocks are sown in the seedbeds manually, in grooves, with a separation of 5 cm between rows, using black peat as substrate mixed with a slow-release NPK fertiliser. The seedlings are sprayed with a fungicide once a week from July to September. Irrigation is applied on demand by controlling the pH, electrical conductivity, and amount of drainage with high-density micro-sprinklers placed on the roof. Subsequently, when the seedling reaches 25 cm high or more, approximately seven months after sowing, they are transplanted into pots. Only the best seedlings are transplanted, that is, erect seedlings, not branched, with straight and tap roots, involving around 20% discards.

Pot cultivation is carried out in 5 L pots specifically designed for this use, made from recycled polyethene (HDPE) from disused orchard pipes, whose shape is an inverted truncated pyramid with a large drainage opening and internal ribs to direct the roots. Substrate composition is relevant in nursery cultivation, and each company has its recipe according to its needs and availability. The substrate used in the nursery consists of 65% white peat, 25% black peat, and 10% perlite. Different pesticides and fertilisers are applied during this stage, as detailed in SM1 Table S1. Slow-release NPK fertilisers are initially mixed with the substrate, and the rest are applied by fertigation and broadcast fertilisation. Those used to correct mineral deficiencies are sprayed by foliar application. Pesticides are sprayed, except for imidacloprid, which is applied with the irrigation water. Insecticides, acaricides and fungicides are used to fight pests or diseases, mainly *Tetranychus urticae* and *Phytophthora*. Drip irrigation is carried out with 4-way pressure-compensated drippers with a flow rate of 2 L/h to obtain drainage, electrical conductivity, and pH values within the established ranges.

Irrigation water for seedbeds and pot cultivation is pumped from a well approximately 30 m deep with an electric pump. A particularity of the water in the area is its high pH (about 9); sulfuric acid is thus added (2.4 L per 10 m^3 of water) to lower it to 5.5–6, following recommendations for citrus seedlings. The irrigation system is an open circuit without recirculation of drained water, which is considered to return to the original basin. A John Deere 50D tractor fuelled by diesel transports the substrates and the ready-to-go seedlings to the nursery gate. A backpack sprayer with a wind turbine and a petrol engine is used to apply pesticides.

2.2. Life cycle assessment

2.2.1. Functional unit and system boundaries

Since the primary function of nurseries is supplying seedlings to the orchards, the functional unit is one seedling 28–32-month-old at the nursery gate ready to be transplanted. As the treatment given to mandarin and lemon seedlings is the same, both species are considered jointly in the analysis. At the studied nursery, a finished seedling must have well-branched secondary and tertiary roots distributed throughout the substrate volume without presenting coils. In addition, the graft must show erect growth and be located 10–20 cm from the base. The stem must be lignified without gum exudation, and the leaves must not show symptoms of nutritional deficiencies or diseases. As mentioned in section 2.1, this is achieved approximately 28–32 months after sowing, except for early seedlings, which are ready after 17–19 months.

The system boundaries are set from cradle to nursery gate, and the stages considered can be seen in Fig. 1 and are detailed in section 2.2.2. As to the temporal system boundaries, data was obtained for 2017, 2018 and 2019. To follow the entire cycle in detail by month, all the greenhouses in which the complete in-pot cycle was carried out in those years were included in the study, as this stage exhibits the greatest variability in agricultural practices, involving a total of 15 greenhouses.

2.2.2. Life cycle inventory (LCI)

For the LCI development, primary data provided by the nursery managers was essential, as the inventory is detailed by month for each of the 15 greenhouses studied. The primary information included details about agricultural practices, such as the number of seedlings transplanted from each greenhouse to the orchard, the type, dosage, and application method of fertilisers and pesticides, the composition and quantity of the substrate, the volume of water applied for irrigation, and the amount of fuel required for both the tractor and backpack sprayers. Additionally, information about all materials used for the internal and external structures of the greenhouses was provided. Inventory data for the citrus nursery stage is shown in Table 1, with further details in SM1 Tables S1 and S2. Relevant background data was taken from Ecoinvent 3.8. database (Moreno Ruiz et al., 2021; Wernet et al., 2016) to develop reference LCI datasets for the LCA models, described in SM1 Table S3.

2.2.2.1. Greenhouse structures. The structure of the greenhouses is a multi-tunnel made up of 2 tunnels with lateral and upper-frontal ventilation openings and a double-door antechamber. The main characteristics of the greenhouses are described in SM2 S1, and the materials used along with their life spans are gathered in SM1 Table S2. Two of the 31 greenhouses of the nursery contain seedbeds, and the remaining ones are intended for pot growing. The internal structures of both kinds of greenhouses and the substrates used are described in SM2 S1.

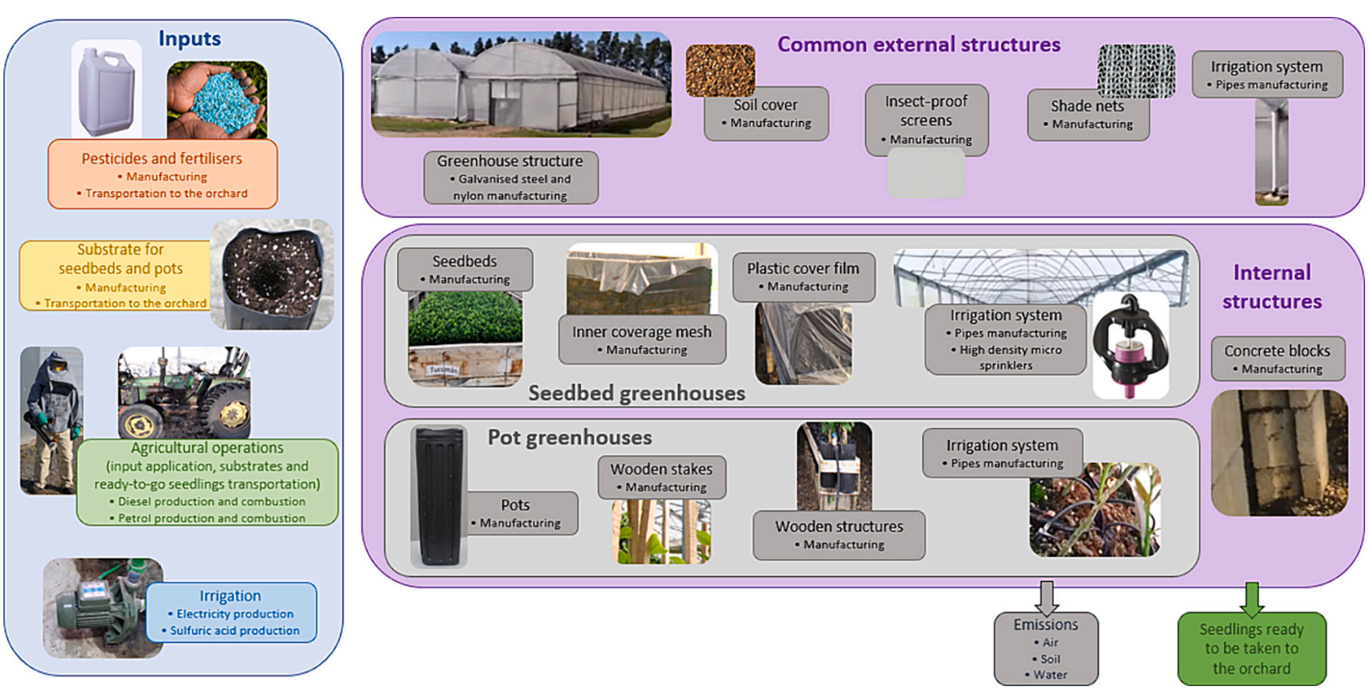

Fig. 1. System boundaries showing the life cycle stages included in the LCA of Uruguayan lemon and mandarin nursery production.

Table 1
Average inventory data for citrus seedling production.

LCI data	Unit	Average	Standard deviation
Production	seedling · $cycle^{-1}$	6882.3	190.6
Water withdrawal for irrigation	$m^3 \cdot seedling^{-1} \cdot cycle^{-1}$	$7.5{\cdot}10^{-2}$	$1.0{\cdot}10^{-2}$
Electricity for irrigation	$kWh \cdot seedling^{-1} \cdot cycle^{-1}$	$1.6{\cdot}10^{-2}$	$2.2{\cdot}10^{-3}$
Diesel for transporting substrates and finished seedlings	$L \cdot seedling^{-1} \cdot cycle^{-1}$	$1.2{\cdot}10^{-2}$	$3.2{\cdot}10^{-3}$
Petrol for the application of phytosanitary products with backpack sprayers	$L \cdot seedling^{-1} \cdot cycle^{-1}$	$5.8{\cdot}10^{-3}$	$1.0{\cdot}10^{-3}$
Substrates			
Peat, seedbeds stage	$m^3 \cdot seedling^{-1} \cdot cycle^{-1}$	$3.9{\cdot}10^{-4}$	$1.1{\cdot}10^{-5}$
Peat, pots stage	$m^3 \cdot seedling^{-1} \cdot cycle^{-1}$	$4.7{\cdot}10^{-3}$	$4.5{\cdot}10^{-5}$
Perlite, pots stage	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$4.7{\cdot}10^{-2}$	$4.5{\cdot}10^{-4}$
Fertilisers			
N	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$5.2{\cdot}10^{-3}$	$7.1{\cdot}10^{-4}$
P_2O_5	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$2.8{\cdot}10^{-3}$	$4.5{\cdot}10^{-4}$
K_2O	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$3.7{\cdot}10^{-3}$	$6.4{\cdot}10^{-4}$
Fungicides	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$8.3{\cdot}10^{-4}$	$2.8{\cdot}10^{-4}$
Insecticides	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$2.5{\cdot}10^{-4}$	$1.1{\cdot}10^{-4}$
Acaricide	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$3.2{\cdot}10^{-6}$	$6.6{\cdot}10^{-7}$
On-field emissions			
N_2O volatilised	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$2.5{\cdot}10^{-4}$	$3.1{\cdot}10^{-5}$
NH_3 volatilised	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$3.7{\cdot}10^{-4}$	$4.7{\cdot}10^{-5}$
NO_2 volatilised	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$2.2{\cdot}10^{-4}$	$2.8{\cdot}10^{-5}$
NO_3^- leached	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$1.2{\cdot}10^{-2}$	$4.1{\cdot}10^{-3}$
PO_4^{3-} leached	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	$3.0{\cdot}10^{-7}$	0.0
Greenhouse surface	$m^2 \cdot seedling^{-1} \cdot cycle^{-1}$	15.3	0.4
Greenhouse materials (allocated to 1 seedling)			
Concrete	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	446.2	–
Crushed stone	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	1636.3	–
High-Density Polyethylene	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	3.4	–
Low-Density Polyethylene	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	6.9	–
Nylon 150 μm	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	5.7	–
Planed softwood	$m^3 \cdot seedling^{-1} \cdot cycle^{-1}$	0.0	–
Polyvinylchloride	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	11.5	–
Raw softwood	$m^3 \cdot seedling^{-1} \cdot cycle^{-1}$	0.7	–
Recycled High-Density Polyethylene	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	0.2	–
Steel	$kg \cdot seedling^{-1} \cdot cycle^{-1}$	1981.1	–
Zinc coating	$m^2 \cdot seedling^{-1} \cdot cycle^{-1}$	12.9	–

2.2.2.2. Production and transportation of agricultural inputs. Data on substrate, fertiliser, and pesticide production was taken from Ecoinvent 3.8, and details are provided in SM2 S2. Input transportation was modelled considering the quantities and distances transported (SM1 Table S4) using Ecoinvent 3.8. A lorry with a 16–32 metric tonne payload was chosen, and for ship transport, a container ship (SM1 Table S3).

2.2.2.3. Fertiliser emissions. In the case study, fertilisers are applied in several ways. Slow-release granular fertilisers are added with the substrate at the beginning of both phases (seedbeds and pots). Then, depending on the crop requirements, fertilisers are applied by fertigation, foliar application, and broadcast fertilisation. For slow-release fertilisers, and based on the supplier's specifications, the nutrient release was modelled linearly for the next five months after its application for the seedbed phase (as it begins in winter when the release of nutrients is slow due to the low temperature) and for three months for the pot phase (which starts in summer, when nutrient release is faster). Following Antón et al. (2019) recommendations, a monthly balance of N and P_2O_5 was performed considering the nutrients provided by fertilisers and irrigation, N and P_2O_5 seedling uptake, leaching, and air emissions. To model N and P_2O_5 absorption by the seedling, the monthly distribution of nutrients proposed by Quiñones et al. (2010) was adapted to the climatic seasons in Uruguay. In this way, the monthly quantity of nutrients consumed by the seedlings was calculated as fractions of their net annual requirements.

To model N_2O emissions in soilless substrate systems, the EF proposed by Pitton et al. (2021) was used. In that study, the authors analyse the emissions of a Douglas fir (*Pseudotsuga menziesii*) cultivated in a bark-based substrate containing a controlled-release fertiliser, with varying doses of the fertiliser applied. The authors observed that N_2O is the major greenhouse gas from a soilless substrate. Although the product system is not the same as the one in this case study, it is also a perennial tree with an organic substrate with slow-release fertilisers incorporated, to which broadcast fertilisation is applied. As the average N used by broadcast fertilisation in this study is low (2.31 g N·$seedling^{-1}$, on average), the EF corresponding to the treatment with 5 g of fertiliser added to the surface of the substrate was used, which corresponds to 2.84% N-N_2O·N $applied^{-1}$.

NH_3 and NO_x were estimated following EMEP/EEA (EEA, 2019), considering normal soil pH and temperate climate as, to the author's knowledge, no study has been published that models these emissions for soilless crops. The amount of NO_3^- leached was then calculated from an N balance as follows:

$$NO_3^-\ leached = Nadded_{fertilisation+irrigation} - Nuptake - N_2O - NH_3 - NO_x$$

As for phosphorus emissions, only phosphate (PO_4^{3-}) leaching was accounted for following the WFLDB guidelines (Nemecek et al., 2019). Considering the system characteristics, soil erosion and phosphate runoff are negligible.

Heavy metal emissions from fertiliser use were considered null at this stage, as the substrate is brought with the seedling to the orchard and incorporated into the soil. Thus, these emissions are most likely to occur in the orchard stage, which is outside the system boundaries of the present study.

2.2.2.4. Pesticide emissions. Emissions from pesticide application were modelled following Antón et al. (2019) recommendations for soilless cultivation. Pesticide emissions to air due to the drift fraction exiting the greenhouse are estimated to be 5% of the average amount applied, as pesticides are applied with the greenhouse vents closed. For modelling the secondary distribution of these emissions, Nemecek et al. (2022) recommendations were followed, using the geographical ratio between surface water and soil of Uruguay, which is 0,007 (CIA, 2023). Soil emissions were considered null. Therefore, emissions to the crop surface represent 95% of the average amount applied. Regarding the secondary distribution of these emissions, two relevant characteristics of the pesticides must be considered. First, most of them have a dissipation rate on plant matrix (RL_{50}) of days or even hours (SM1 Table S5a), meaning that the absorption process by the plant is almost immediate. And second, in general, they all have low vapour pressures (SM1 Table S5b), so the plant-air secondary distribution is considered minimal. Therefore, counting the long cycle in which the seedlings are inside the greenhouse, the remaining pesticides are considered degraded and hence do not reach environmental compartments nor represent emissions in the inventory.

2.2.2.5. Water and energy consumption for irrigation. For calculating the water applied during the productive cycle, the information on the number and duration of irrigations according to the climatic season and the stage of the crop was used. For seedbed cultivation, 30 min irrigations once a week were accounted for in October and 60 min twice a week in November and December. For cultivation in pots, seven weekly irrigations of 30 min were considered in summer, three weekly irrigations of 20 min in winter and four weekly irrigations of 20 min in spring and autumn. The water consumed by the crop was calculated through a water balance as the difference between inputs (irrigation) and outputs (drainage). The recommended drainage was provided by the nursery responsible and is between 3 and 5% for the seedbed cultivation stage and 5–20% for the pot stage. For the case study, the most conservative hypothesis was adopted; thus, the minimum of both drainage ranges (maximum water consumption of the seedling) was used.

The energy used to pump the water was calculated using the eq. (1):

$$E = P \cdot V \cdot \rho \cdot g \cdot 1.3 \quad (1)$$

Where E is the energy needed for irrigation (J); P is the pressure necessary to carry out the irrigation (m of water column), which in the case study is the 60 m w.c. (30 m w.c. to elevate the water from the well, and 30 m w.c. needed in the irrigation head); V is the volume of irrigation water (L), ρ the density of the water ($1\ kg \cdot L^{-1}$), and g is the acceleration of gravity ($9.807\ N \cdot kg^{-1}$). The energy required for irrigation is oversized by 30% to consider the pump performance and the losses in the water channelling to the irrigation head.

2.2.2.6. Data uncertainty. The Pedigree Matrix (Weidema and Wesnæs, 1996) was used to qualitatively assess the data's uncertainty. As to the reliability, completeness, and temporal correlation, the data complies with level 2 of the matrix since it was provided by the responsible for the orchard from a small number of sites (1 nursery) during adequate periods (sufficient to quantify the complete greenhouse cycle), and with less than six years of difference concerning the year of the study. Regarding the geographical and technological correlation, most of the data correspond to level 1 of the matrix, as the data was obtained directly from the nursery in the study area. These values meet the data quality objectives of the study (see SM1 Table S6).

2.2.3. Impact categories and impact assessment methods

To quantify the environmental impacts, EN 15804 + A2 impact assessment was used, following EPD (2023) recommendations, which proposes a default list of environmental performance indicators, whose CF are based on the "EN 15804 reference package" provided by the Joint Research Centre (EC, 2023). Therefore, the impact categories assessed are climate change (CC), acidification (Ac), freshwater, marine and terrestrial eutrophication (FEu, MEu and TEu), photochemical ozone formation (impacts on human health) (POFhh), ozone depletion (OD), resource use of minerals and metals and fossils (RUm and RUf), and blue water scarcity (BWS). Freshwater ecotoxicity (ET) and human toxicity carcinogenic and non-carcinogenic (HTc and HTnc) were assessed using USEtox 2.12 (Rosenbaum et al., 2008). Characterisation factors (CFs) available in the USEtox 2.12 database were used for the pesticides applied, except for abamectin, for which the CF for avermectin B1A was used.

To calculate the direct BWS impact due to irrigation, specific monthly CFs for the corresponding Uruguayan basin were used (Google Earth, 2023). As for fertilisers, pesticides, and substrates production, as their origin is known, AWARE CFs for non-agricultural activities, retrieved from WULCA (2023) for the corresponding producing country, were used (see SM1 Table S7). The world average CF for non-agricultural activities was selected for the remaining indirect water consumption.

2.2.4. Relative contribution of the nursery process to the whole crop cycle

To estimate the relative contribution of the nursery process to the whole citrus crop cycle, the growing stages of the tree must be considered. The cycle starts with the nursery stage, which usually lasts over two years, as commented in section 2.1. In the third year, the tree is transplanted to the orchard, where it does not produce citrus fruits for about three years but consumes inputs (non-productive stage). The tree begins to bear fruit gradually during the next three years (increasing yield stage). In the seventh year, the tree reaches the full production stage, and the yield is at its maximum. This stage lasts approximately 20 years, followed by the senescence phase, in which the yield begins to decrease, and the treetop is renewed for economic reasons (Fig. 2).

Currently, no research is available on the environmental impacts of the low production stage of Uruguayan citrus fruits, that is, the non-productive and increasing yield stages. Thus, in the present study, a rough estimate of the impacts of this stage is made as a percentage of those of the full production stage since most of the environmental impacts in the tree cycle are closely linked to the quantity of inputs applied (i.e., impacts related to the production and transportation of inputs, machinery operations for input application, or on-field emissions). Therefore, this percentage is calculated considering the amount of inputs added during the years of low production, those added in the years of full production and the yields obtained in each stage.

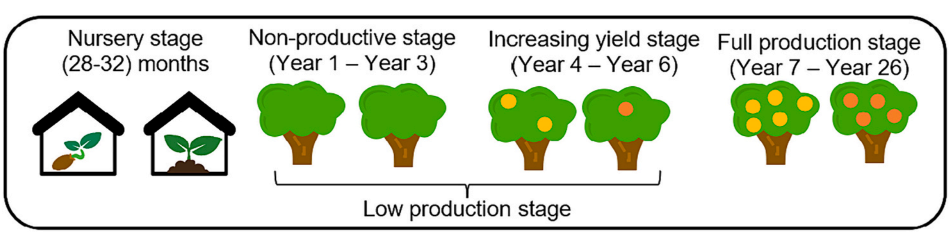

Fig. 2. Representation of the citrus crop cycle.

Table 2
Input consumption and yield of the low and full production stages.

	N ($kg \cdot tree^{-1}$)	P_2O_5 ($kg \cdot tree^{-1}$)	K_2O ($kg \cdot tree^{-1}$)	Pesticides ($kg \cdot tree^{-1}$)	Average yield ($ton \cdot ha^{-1}$)
Year 1	$2.3 \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$	$2.3 \cdot 10^{-2}$	$1.8 \cdot 10^{-1}$	0
Year 2	$9.2 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$7.2 \cdot 10^{-2}$	$1.8 \cdot 10^{-1}$	0
Year 3	$9.2 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$7.2 \cdot 10^{-2}$	$1.8 \cdot 10^{-1}$	0
Year 4	$9.2 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$7.2 \cdot 10^{-2}$	$1.9 \cdot 10^{-1}$	8
Year 5	$9.2 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$7.2 \cdot 10^{-2}$	$1.9 \cdot 10^{-1}$	16
Year 6	$9.2 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$7.2 \cdot 10^{-2}$	$2.4 \cdot 10^{-1}$	32
Year of full production (mandarins)	$1.2 \cdot 10^{-1}$	$1.4 \cdot 10^{-3}$	$7.1 \cdot 10^{-2}$	$1.8 \cdot 10^{-1}$	36
Year of full production (lemons)	$3.9 \cdot 10^{-1}$	$1.6 \cdot 10^{-2}$	$2.8 \cdot 10^{-1}$	$9.7 \cdot 10^{-1}$	56

Specifically, the quantity (kg) of inputs applied per kg of citrus fruits produced in the low production stage of the crop is divided by the years of full production (20 years for Uruguayan citrus) to understand its weight per year of full production. This value is then divided by the kg of inputs applied per kg of citrus fruits produced per year in the full production stage and multiplied by 100. The values obtained are 12% for lemons and 18% for mandarins. To make this estimation, data on the inputs (nutrients and pesticides) applied in the full production stage was retrieved for lemons and mandarins from Cabot et al. (2023a) and Cabot et al. (2023b), respectively. For the low production stage, data concerning input consumption and yields was provided by an expert. A summary of the inventory data is shown in Table 2.

Since the impacts of the nursery stage are calculated per seedling, those of the low and full production stages must also be calculated per tree. For this, the environmental impacts of the full production stage per hectare and the tree density (516 trees·ha^{-1} for lemons and 557 trees·ha^{-1} for mandarins) are used, retrieved from Cabot et al. (2023a), and Cabot et al. (2023b), and the impacts of the low production stage per citrus tree are estimated as follows:

$$\frac{impact\ per\ ha_{FullProduction}\cdot\frac{surface\ (ha)}{tree\ density}}{yield_{FullProduction}}\cdot 0.12=\frac{impact\ per\ tree_{LowProduction}}{yield_{LowProduction}}\ for\ lemons$$

$$\frac{impact\ per\ ha_{FullProduction}\cdot\frac{surface\ (ha)}{tree\ density}}{yield_{FullProduction}}\cdot 0.18=\frac{impact\ per\ tree_{LowProduction}}{yield_{LowProduction}}\ for\ mandarins$$

Finally, the contribution of the impacts of the nursery stage is estimated as follows:

$$\frac{impact\ per\ tree_{NurseryStage}}{impact\ per\ tree_{NurseryStage}+impact\ per\ tree_{LowProductionYears}+impact\ per\ tree_{FullProductionYears}}$$

A summary of the impacts per tree for all crop stages can be seen in SM1 Tables S8a and S8b.

3. Results and discussion

3.1. Environmental impacts and alternatives for improvement

The environmental impact scores at the nursery stage for the impact categories assessed, calculated as the average of the 15 greenhouses analysed, are shown in Table 3, along with their arithmetic standard deviations. The average values of each stage assessed and their standard deviations are shown in SM1 Table S9.

When analysing the relative contribution of the cradle-to-nursery gate stages, infrastructure and input transportation stand out as a hotspot in most impact categories assessed (Fig. 3), mainly due to the production of the galvanised steel structures and peat transportation by ship. The impact scores exhibit a low variability, with coefficients of variation (CV) between 2% and 8% depending on the impact category due to the low variability of those processes. Infrastructure production presents a CV of 2%–3% depending on the impact category, mainly associated with the number of plants leaving each greenhouse. The CV of peat transportation is 1% for all the impact categories. MEu shows the maximum variability (CV = 8%) due to the high variability of the NO_3^- leachate (CV = 34%).

From the results, evaluating potential alternatives to reduce the impacts involving the infrastructure and substrate becomes relevant. Considering that the greenhouse structure is already set, and the substrates' composition is based on previous suitability evaluations, the effect of extending the life span assigned to these inputs is analysed. Based on the literature, a 15-year lifespan has been considered for the galvanised steel structure (SM1 Table S2). Since these structures tend to last longer in practice, an extension of 10 years has been analysed. Regarding the substrate, it must be borne in mind that only the substrate of the seedbeds could be reused, as the one of the pots goes to the orchard with the seedlings. Hence, duplicating the life span of the seedbed substrate represents an interesting choice to be analysed. Another alternative is to reduce the peat transportation distance, as it is currently brought from Lithuania, studying suppliers closer to the nursery. The most relevant peat producers are in the northern hemisphere (MarketWatch, 2023), and the nearest is Ireland. Changing the supplier from Lithuania to Ireland would imply a 20% reduction in the travelled distance (Searates, 2023).

Table 3
Environmental impacts of producing one seedling in a citrus nursery (average scores and arithmetic standard deviation).

Climate change (kg CO_2 eq.·seedling^{-1})	4.0 ± 0.1
Ozone depletion (kg CFC11 eq.·seedling^{-1})	$2.0\cdot10^{-7}$ ± $8.9\cdot10^{-9}$
Acidification (Mole of H+ eq.·seedling^{-1})	$4.5\cdot10^{-2}$ ± $9.8\cdot10^{-4}$
Freshwater eutrophication (kg P eq.·seedling^{-1})	$8.9\cdot10^{-4}$ ± $2.6\cdot10^{-5}$
Marine eutrophication (kg N eq.·seedling^{-1})	$1.4\cdot10^{-2}$ ± $1.2\cdot10^{-3}$
Terrestrial eutrophication (Mole of N eq.·seedling^{-1})	$1.2\cdot10^{-1}$ ± $2.8\cdot10^{-3}$
Photochemical ozone formation, human health (kg NMVOC eq.·seedling^{-1})	$3.3\cdot10^{-2}$ ± $6.8\cdot10^{-4}$
Resource use, mineral and metals (kg Sb eq.·seedling^{-1})	$2.7\cdot10^{-5}$ ± $1.1\cdot10^{-6}$
Resource use, fossils (MJ·seedling^{-1})	$5.8\cdot10^{1}$ ± 1.5
Ecotoxicity (CTUe·seedling^{-1})	$1.3\cdot10^{4}$ ± $4.1\cdot10^{2}$
Human toxicity, cancer (CTUh·seedling^{-1})	$9.0\cdot10^{-6}$ ± $2.6\cdot10^{-7}$
Human toxicity, non-canc. (CTUh·seedling^{-1})	$1.9\cdot10^{-6}$ ± $7.4\cdot10^{-8}$
Blue water scarcity (m^3eq.·seedling^{-1})	1.5 ± $4.7\cdot10^{-2}$

Of the studied alternatives, the reuse of the seedbed substrate has a negligible influence on the impact scores, generating reductions of 0 to 3% in the different impact categories, where the greatest reduction is observed in Ac, TEu and POFhh, mainly due to the decrease in the associated transport. The 10-year increase in the life span of structures reduces considerably almost all the assessed categories (Fig. 4a). Among them, the three related to toxicity stand out, with cuts of 28%, 39% and 31% in ET, HTc and HTnc, respectively (Fig. 4a). In addition, the reductions in BWS, FEu and RUm are around 28%. Reducing the transportation distance of the substrate by 20% mainly affects Ac, TEu and POFhh, which decrease by 13%, 14% and 14%, respectively (Fig. 4b). MEu, OD, and CC impact categories are also reduced by 11%, 7% and 6%, respectively. In summary, these two alternatives represent a good option to reduce the impacts of the nursery stage. However, the effect of increasing 10-year the life span of structures is more relevant to the impact results.

It is worth mentioning that even though the substrate mix was carefully tested and selected in the nursery analysed, it is mostly peat, and peatlands are vital ecosystems that are in danger. The Global Peatlands Assessment (UN, 2022) remarks that peatlands are being

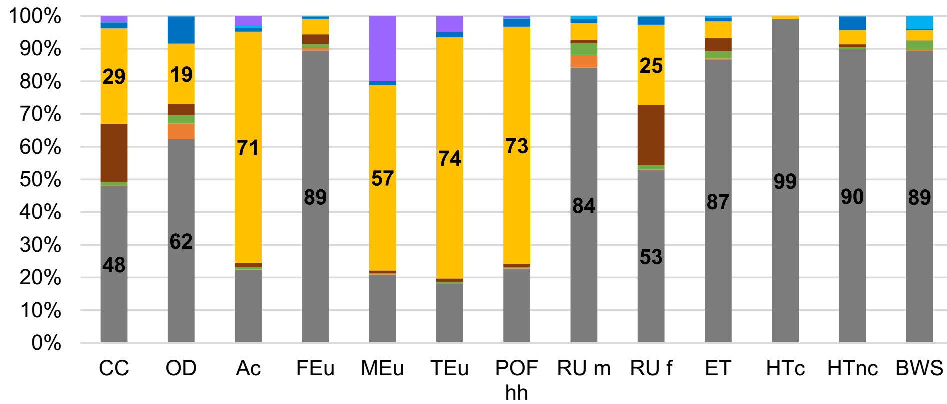

Fig. 3. Average percentual contribution of the life cycle stages to the environmental footprint of Uruguayan citrus nursery production. ■ Infrastructure, ■ Transport, ■ Pesticides production, ■ Machinery operations, ■ Fertilisers production, ■ Irrigation, ■ Substrates production, ■ On-field emissions. Climate Change (CC), Ozone Depletion (OD), Acidification (Ac), Freshwater Eutrophication (FEu), Marine Eutrophication (MEu), Terrestrial Eutrophication (TEu), Photochemical Ozone Formation impacts on human health (POFhh), Resource Use - minerals and metals - (RUm), Resource Use - fossils - (RUf), Ecotoxicity (ET), Human Toxicity - cancer (HTc), Human Toxicity - non-cancer (HTnc), Blue Water Scarcity (BWS). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

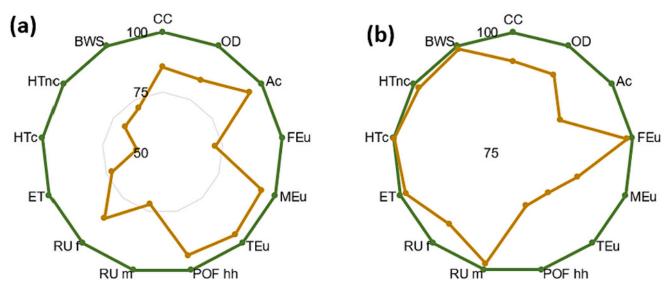

Fig. 4. **(a)** Radial plots representing percentage improvement for the 10-year increase in the life span of structures per impact category. **(b)** Radial plots representing percentage improvement for a reduction in 20% of the transport distance of the substrate per impact category. Green values are for the initial situation, and brown for the improvement alternative. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

degraded worldwide, and one of the leading causes is their use in agriculture. It is essential to conserve, restore and sustainably manage peatlands as they play a vital role in the water cycle by storing and filtering water, and they provide shelter to unique plants and animals. Furthermore, peatlands contain up to one-third of the world's soil carbon (UN, 2022). Hence, keeping this carbon locked away is critical to achieving global climate goals, and exploring novel substrate combinations that do not rely on peat is recommended. Recent research suggests that peat-free alternatives, such as composted organic wastes, coir pith, or biochar, hold great potential as substitutes for soilless cultivation (Atzori et al., 2021; Barrett et al., 2016). Nevertheless, in the case of fruit seedlings, it is essential to prioritise alternatives that do not compromise their well-being, as this is a crucial aspect of production standards (INASE, 2021).

3.2. Contribution of the environmental impacts of the nursery stage on the whole crop cycle

For lemons, the full production stage accounts for 98.7–99.4% of the impacts of the cycle, depending on the impact category, and for mandarins, it represents 95.1–98.4%. Hence, the impacts of the nursery and low production stages are almost negligible. The low production stage accounts for 0.6% of the impacts for lemons and 1.4% for mandarins. As to the nursery stage, in the case of lemons accounts for 0.0–0.7% of the impact scores, depending on the category, and for mandarins 0.2–3.6%. However, this is not the case for HTc. Due to the significant toxicity associated with the production of galvanised steel for greenhouse structures and the lack of available characterisation factors (or equalling zero) in the USEtox 2.12 database for all pesticides used in the orchard, the nursery stage represents 14.4% of the HTc impacts in the case of lemons and 50.3% in the case of mandarins.

The literature on perennial fruit trees also highlights the low contribution of the nursery stage to the total tree cycle. For French apple seedlings in open field, it ranges from 0.2 to 2.6% (Alaphilippe et al., 2016). Brito De Figueirêdo et al. (2016) also report a small contribution of the nursery stage in a study on Brazilian cashew production. Cashews are grown in greenhouses using a substrate, as in the present study, although the substrate transport and the production of the greenhouse structure are not modelled. In addition, the seedling's cycle lasts 90–100 days, whereas that of citrus lasts more than two years. Bessou et al. (2016) also agree that the impacts of the nursery stage are negligible for small citrus trees produced in Morocco except for terrestrial ecotoxicity, where the emissions from abamectin application stand out. In any case, the authors do not give details of the inventory for this stage or mention the use of substrate or greenhouses.

3.3. Comparison with processes in databases

Considering the gap detected in the LCA literature on nurseries of citrus seedlings, the results of this study have been compared with those proposed in two widely known databases, Agribalyse® v3.0.1 (Agribalyse, 2023) and Ecoinvent 3.8. (Moreno Ruiz et al., 2021; Wernet et al., 2016). Specifically, the processes selected are "Clementine, tree seedling (phase), Souss, at tree nursery – MA" from Agribalyse® v3.0.1 and "RoW: fruit tree seedling production, for planting" from Ecoinvent 3.8, as there is not a specific process for citrus fruit production. The impact scores obtained in the present study are, on average, 10 times higher than those of Ecoinvent 3.8 and 400 times higher than those of Agribalyse® v3.0.1 in almost all impact categories assessed (SM1 Table S10).

The rationale behind these differences lies mainly in how the processes were modelled. In both databases, nurseries are open-field, without irrigation, greenhouse, or substrate, which significantly differs from the typical citrus nursery. In Ecoinvent 3.8, the process lasts one year, and in this case study, the seedlings leave the nursery after 28–32 months. The agricultural inputs differ as to the type of products and dose applied. In the present study, 13 fertilisers and 8 pesticides are modelled, while, for example, in Agribalyse® v3.0.1, the production of only two fertilisers and a single generic pesticide are modelled. The transportation of inputs (a relevant hotspot) is not considered in

Ecoinvent 3.8 and is modelled in Agribalyse® v3.0.1 using a tractor with a trailer. Therefore, it probably refers to its transport within the farm and not from the origin country. Emissions from fertilisers and pesticides are calculated in the present study using different approaches (see section 2.2.2.). In Ecoinvent 3.8, the former are modelled following SALCA and in Agribalyse® v3.0.1, following IPCC, EMEP and WFLDB. As for the latter, no information is provided on how these emissions are modelled in databases.

3.4. Water and emissions modelling in greenhouses

As commented in the introduction, accurately modelling the water consumption and emissions of fertilisers and pesticides in greenhouses, particularly for soilless crops, is a complex task in LCA studies. The present study aims to contribute to this aspect. The equations designed by Allen et al. (1998) to measure on-field crop evapotranspiration are not suitable for greenhouse cultivation, as the seedlings are not exposed to the same conditions considered while creating the model. Modifications to this equation have been suggested, mainly for vegetable production in greenhouses, which are discussed in the review by Incrocci et al. (2020). However, these equations could not be applied in the current study as the crop is a perennial fruit. Also, specific parameters, such as the crop coefficient (Kc), were not available data. Therefore, an interesting alternative to modelling the water consumption of seedlings is developing water balances that consider all the inputs and outputs of the system, preferably on a daily or monthly basis. Regarding pesticide emissions, standardised models such as PestLCI cannot be applied to greenhouse cultivation at the moment, as they are designed for open environments. Thus, as recommended by Antón et al. (2019), practitioners should model these emissions based on factors such as the method of pesticide application (closed or open vents) and the growing medium (soil or substrate). As well, the dynamics between the environmental compartments within the greenhouse gain significance, and two crucial pesticide characteristics that must be considered are highlighted: dissipation rate on the plant matrix and vapour pressures. Fertiliser emissions are also influenced by factors such as how and when it is applied, the type of compound, whether it is a closed or open loop system and nutrient uptake, which varies according to the growth stage. Particularly, nitrogen emissions modelling in soilless crops represents a challenge due to the limited literature on the subject. For example, EFs from Tier 1 methods, like those proposed in IPCC (2019), should not be applied as they are proposed for soil cultivation and are significantly lower than those obtained, for example, for N_2O in previous research (Pitton et al., 2021). Therefore, there is a compelling need to develop EFs tailored to soilless crops based on the type of substrate used. In this line, the application of adequately calibrated Tier 3 methodologies such as DNDC (University of New Hampshire, 2007) or LEACHN (Hutson and Wagenet, 1992) comes as an interesting option to model these emissions, as they take into account several system parameters.

3.5. Limitations of the study

Among the main limitations of the present study lies the challenge of accurately calculating the impacts of the low production stage of the crop as, due to a lack of data, they had to be estimated. To address this issue, further research should be conducted in the country with a specific focus on these stages. This would help validate the findings of the present study and provide a more comprehensive understanding of the subject. Additionally, while nursery production is standardised, we acknowledge that a larger sample size of nurseries from various regions of the country could be beneficial for detecting potential differences and conducting statistical analyses. Another limitation involves the quantification of nutrient absorption by the seedlings. In the present study, Spanish coefficients adapted to Uruguayan climatic seasons are used, which may not accurately reflect local conditions. Therefore, the development of studies that quantify the N and P_2O_5 absorption coefficients of citrus seedlings in Uruguayan greenhouses is encouraged.

4. Conclusions

An approach to quantifying the environmental impacts of citrus fruit tree nurseries was performed using LCA, studying a representative nursery located in the south of Uruguay. The main hotspots detected are infrastructure production and input transportation, mainly because of substrate transportation. Alternatives to reduce both impacts are proposed. Results highlight that the contribution of the nursery stage to the environmental impacts of the whole citrus productive cycle is negligible (0–3.6%) in all impact categories except cancer human toxicity. High differences arise when comparing the results with those from commercial databases since, in the latter, open-field nurseries are considered; thus, the use of substrates or infrastructure is not accounted for, obtaining lower impact scores that are not representative of citrus fruit nurseries. From the methodological point of view, several issues arise from this study. On the one hand, the need to develop models or emission factors for fertiliser emissions in soilless crops is identified, which is specifically relevant for citrus fruit tree seedlings, considering the time they remain in the greenhouse. On the other hand, there is also a need to harmonise water consumption modelling for soilless perennial crops in greenhouses. And finally, as to pesticide emissions, the possibility of including cultivation in greenhouses in standardised models like pestLCI is highlighted. The harmonisation of these methods would be beneficial to calculate the impacts of soilless production in greenhouse systems in general, not only in nurseries. The present study seeks to contribute to the development of citrus and perennial fruits LCAs, analysing the nursery stage in detail and incorporating primary data. It provides scientific and quantitative evidence of its contribution to the production cycle to understand where the measures to promote sustainable production of fruits in general, and in particular of citrus fruits, should be aimed in line with SDG 12.

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CRediT authorship contribution statement

María Inés Cabot: Conceptualization, Methodology, Software, Formal analysis, Data curation, Writing – original draft, Investigation. **Joanna Lado:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Matías Manzi:** Writing – review & editing. **Neus Sanjuán:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing.

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.

Data availability

The data used in this study is fully available and reported in the main article and supplementary materials.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eiar.2024.107488.

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