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IDENTIFYING DATA FOR HORTICULTURE CATEGORIES TO PROPOSE A STANDARD CARBON FOOTPRINT MODEL

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ABSTRACT

This study aims to identify the data requirements for horticulture categories to propose a standard carbon footprint model. Focusing on the specific case of strawberry production, the research questions addressed are: 1) How does the carbon emission footprint of strawberries compare with the HortiFootprint Category Rules (HFCR)? and 2) What are the data requirement themes. To model the carbon emissions of strawberries based on the findings of the first research question?

To attain these objectives, a comprehensive literature review was conducted to gather existing knowledge on the carbon emissions of strawberries. A case study analysis was employed, selecting representative strawberry production cases to analyse their carbon emissions. Primary data was collected through surveys and interviews with strawberry farmers, providing insights into production practices and resource inputs.

Data compilation involved collecting and organizing data from various sources, including government reports, industry databases, and research studies.

The findings of the study were compared with the HFCR through comparative analysis to evaluate the carbon emission footprint of strawberries and identify any gaps or differences in approaches. The comparative analysis facilitated the identification of data requirement themes for modelling the carbon emissions of strawberries.

The results of this study contribute to the development of a standard carbon footprint model for horticulture categories, specifically focusing on strawberries. The identified data requirements can guide future research and support stakeholders in measuring and reducing the environmental impact of strawberry production. Furthermore, the methodology employed in this study can serve as a basis for studying other horticultural products and expanding the proposed carbon footprint model to cover a wider range of categories.

Keywords: carbon footprint, life cycle assessment (LCA), sustainable horticulture, data requirements

CONTENTS

LIST OF ABBREVIATIONS

AI	Artificial intelligence
C	Carbon
$CaCO_3$	Calcium carbonate
CAS	Chemical abstracts service
Cd	Cadmium
CHP	Combined heat and power
CO_2	Carbon dioxide
Cu	Copper
FAO	Food and Agriculture Organization
GHG	Greenhouse gas
HFCR	HortiFootprint Category Rules
HHV	Higher heating value
K	Potassium
LCA	Life cycle assessment
LCI	Life cycle inventory
LHV	Lower heating value
LUC	Land use change
N	Nitrogen
P	Phosphorus
PEF	Product environmental footprint
S	Sulfur
UN	United Nations
Zn	Zinc

1 INTRODUCTION

The horticultural industry is vital for global food production, contributing to food security, economic growth, and employment opportunities. According to a report by the Food and Agriculture Organization (FAO) of the United Nations (UN) (2016), the horticultural industry is worth over $300 billion globally and is projected to experience further growth in the foreseeable future.

One prominent trend in the horticultural industry is the increasing demand for fresh and healthy produce, particularly in developed countries. Consumers are increasingly more conscious of their health and are willing to pay a premium for high-quality fruits and vegetables. There is also a growing demand for organic and sustainable produce, driven by concerns over the use of pesticides and environmental sustainability.

Another trend is the increasing use of technology in horticulture, i.e., sensors, artificial intelligence, and automation, which are expected to drive growth in the industry. Precision farming techniques, e.g., hydroponics, smart irrigation systems, and automated crop monitoring systems (Al-Gaadi et al. 2023) are expected to improve crop yields and reduce water usage, while vertical farming technologies are expected to increase crop productivity in urban areas where space is limited (Sipos et al. 2020, 273; P&S Intelligence 2021). These techniques allow for the production of high-quality produce in controlled environments, using fewer resources.

As the population continues to grow and dietary preferences change, and with the limitations of available agricultural land and increasing environmental pressures, it is essential to enhance vegetable production yields significantly while minimizing their environmental impact (Ronga et al. 2019, 836 - 845; Wang et al. 2020, 254).

While there have been multiple studies investigating the effects of agricultural practices, fertilizer, and land use changes (LUC) on global greenhouse gas (GHG) emissions and potential strategies for mitigation (Ronga et al. 2019, 836 - 845; Parajuli et al. 2022; Perez-Neira & Grollmus-Venegas 2018, 60 - 68; Soode et al. 2015, 169 - 179), research on the impact of horticultural products production is limited (De Jesus Pereira et al. 2021, 282).

The horticulture industry plays a crucial role in meeting the increasing demand for food, fuel, and fiber (UN Food and Agriculture Organization 2016). However, it is also a significant contributor to GHG emissions, which have a major impact on climate change (IPCC 2014). To address this issue, a standard carbon footprint model is needed to help the industry better understand the environmental impact of their products and explore opportunities to minimize their carbon footprint.

The life-cycle approach within the sustainability framework is already being used by many business associations and companies in the industry. It is increasingly used to reduce the overall environmental impact of goods and services across their entire life cycle (Graedel and Allenby 2003, 21 – 30). The approach is also utilized to enhance the competitiveness of the company’s products and to communicate with governmental bodies. Additionally, life-cycle assessment (LCA) is an internationally standardized methodology (ISO 14040) and is a decision-making tool to improve product design by considering factors, i.e., material selection, technology, design criteria, and recycling (Schau and Fet 2007, 255 - 264). LCA facilitates the benchmarking of different product system options, thereby supporting decision-making processes related to purchasing, technology investments, and innovation systems. The use of LCA offers the advantage of providing a comprehensive assessment tool that evaluates the trade-offs associated with environmental pressures, human health, and resource consumption (European Commission 2005.)

The public sector, e.g., employs life cycle thinking in stakeholder consultations and policy implementation. This approach ensures that systematic assessments are conducted, taking into account the borader implications of policies and considering trade-offs both upstream and downstream (Manfredi et al. 2012.)

Aim of this study is to review existing LCA case studies for strawberries and compare them with Hortifootprint Category Rules (HFCR) methodology to identify data parameters for a representative crop, find similarities and identify differences, discuss whether it is possible to create a standard model for carbon emissions calculations.

The aim of the study is to determine:

1. How does the carbon emission footprint of strawberry compare with the HFCR?
2. What is the data requirement themes to model carbon emission of strawberry using findings of R1?

2 LITERATURE REVIEW

The literature review is an essential component of any research study, including the present study on identifying data for horticulture categories to propose a standard carbon footprint model.

2.1 Overview of the horticulture industry and its environmental impact

The horticulture industry involves the cultivation, processing, and sale of fruits, vegetables, flowers, and other plants. It plays an important role in agriculture and the global economy, as it provides food, fiber, and ornamental plants for people worldwide. However, the industry also has significant environmental impacts, including the use of pesticides, fertilizers, water, and energy.

One major environmental impact of horticulture is the use of pesticides. Pesticides are chemical substances utilized to eliminate pests and diseases that pose a threat to plants. While their primary purpose is to protect plants, it is important to acknowledge that pesticides can have detrimental effects on non-target species and have negative effects on the environment. Pesticides can leach into soil and waterways, contaminating the surrounding environment and potentially harming wildlife and human health. (Abrams et al. 1991, 463 - 492; Valdez Salas et al. 2000, 399 - 412; Alavanja et al. 2003, 800 - 814; Pimentel et al. 2005, 573 - 582; Pretty & Bharucha 2015, 152 - 182; Sarkar et al. 2021.)

Another significant impact of horticulture is the use of fertilizers (Dhankhar and Kumar 2023). Fertilizers are substances used to provide plants with vital nutrients, but excessive use of fertilizers can lead to soil degradation, water pollution, and GHG emissions (Al-Gaadi et al. 2023). Nitrogen (N) fertilizers, e.g., can release nitrous oxide, a potent GHG that contributes to climate change (Wallman et al. 2022, 337; Peixoto and Petersen 2023, 32; Xu et al. 2023, 188).

Water is, e.g., crucial resource in horticulture, and the industry’s use of water can have significant environmental impacts (Wrobel-Jedrzejewska et al. 2021, 278). The irrigation systems used in horticulture can cause soil erosion, waterlogging, and water pollution (Sanchez-Martin et al. 2008, 1698 - 1706; Burbano-Figueroa et al. 2022). Additionally, the increasing demand for water in the industry can deplete local water resources and put pressure on water supplies in drought-prone areas.

Finally, the energy used in horticulture can, e.g., have environmental impacts (Ordikhani et al. 2021, 2899 - 2915). Greenhouses require significant amounts of energy for heating and cooling (Roy et al. 2020, 132), which can lead to GHG emissions and contribute to climate change.

2.2 Carbon footprint and its importance in sustainable agriculture

Carbon footprint is a measure of the total GHG emissions caused by human activities, including agriculture, transportation, and industry. In the context of horticulture, carbon footprint refers to the amount of GHG emitted during the production and distribution of horticultural products, i.e., fruits, vegetables, and ornamental plants.

The concept of carbon footprint has gained significant attention in the context of sustainable agriculture. In the agricultural sector, carbon footprint assessment has emerged as a valuable tool for evaluating the environmental impact of agricultural practices and identifying opportunities for reducing emissions.

Reducing the carbon footprint in agriculture is of paramount importance for several reasons. Firstly, agriculture is a significant contributor to global GHG emissions (Food and Agriculture Organization of the UN 2016), accounting for a substantial portion of total emissions worldwide. The production and use of synthetic fertilizers, methane emissions from livestock (Peixoto and Petersen 2023, 32), agricultural machinery, and land-use changes are sources of GHG in agriculture.

Mitigating climate change is a primary objective of reducing the carbon footprint (IPCC 2014) in agriculture. By adopting sustainable practices that minimize emissions, i.e., precision agriculture techniques, organic farming methods (Pimentel et al.2005, 573 - 582; Burbon-Figueroa et al. 2022; Xu et al. 2023, 188), and improved manure management (Peixoto and Petersen 2023, 32), farmers can play a crucial role in mitigating climate change. These practices can contribute to reducing the release of carbon dioxide (CO_2) and other potent GHG into the atmosphere.

Furthermore, reducing the carbon footprint in agriculture is closely linked to soil health and fertility. Sustainable agricultural practices, i.e., conservation tillage (Canali et al. 2013, 11 - 18), cover cropping (Rouge et al. 2023, 295; Singh et al. 2023, 230), and agroforestry, promote carbon sequestration in the soil (Gonzalez-Rosado et al. 2023, 354; Rosinger et al. 2023, 433; Zuo et al. 2023, 382). This process involves capturing atmospheric CO_2 and storing it in the soil as organic matter, enhancing soil quality, and improving its capacity to retain water and nutrients. Carbon sequestration in agricultural soils has the potential to mitigate climate change while simultaneously enhancing soil productivity and resilience.

Biodiversity conservation is another crucial aspect associated with reducing the carbon footprint in agriculture. Sustainable farming practices that promote biodiversity (Acero Triana et al. 2021, 453; Giraldo-Perez et al. 2021), i.e., maintaining diverse crop rotations, planting hedgerows, and creating wildlife-friendly habitats, can provide ecological benefits. Preserving biodiversity helps maintain a balance in ecosystems, enhances natural pest control, and promotes resilience to climate change impacts.

Water conservation is, e.g., intricately linked to reducing the carbon footprint in agriculture. Sustainable water management practices, including efficient irrigation techniques (Sanchez-Martin et al. 2008, 1698 - 1706; Burbano-Figueroa et al. 2022), precision irrigation, and water recycling, can significantly reduce water consumption and associated energy use. By conserving water resources, farmers can contribute to reducing the energy requirements for water pumping and treatment, thereby lowering the carbon footprint.

To effectively reduce the carbon footprint in agriculture, a combination of strategies is required. These include adopting sustainable farming practices, improving resource-use efficiency, implementing renewable energy technologies, enhancing soil carbon sequestration, and promoting agroecological approaches. Furthermore, policy support, financial incentives, and knowledge dissemination are essential for facilitating the adoption of sustainable agricultural practices at a broader scale.

The concept of carbon footprint in agriculture holds great significance in achieving sustainable agriculture and addressing the challenges of climate change. By reducing GHG emissions, enhancing carbon sequestration in soils, promoting biodiversity, and conserving water resources, the agricultural sector can make significant strides towards a more sustainable and resilient future. Efforts to reduce the carbon footprint in agriculture require collaboration among farmers, policymakers, researchers, and consumers to foster a transition towards environmentally friendly and socially responsible agricultural practices.

3 METHODOLOGY

For this study various data collection and analysis methods were employed.

The findings of the case studies and literature review were compared with HFCR through comparative analysis, to evaluate data requirements and identify gaps or differences in approaches. The comparative analysis provided insights into the comprehensiveness and relevance of the proposed data requirements for modeling the carbon emissions of strawberries.

3.1 Literature review

A literature review was conducted to gather existing knowledge and studies on the carbon emissions of strawberries. Scientific databases, journals, conference proceedings, and relevant reports were searched to identify relevant studies, methodologies, and data sources.

Data compilation involved collecting and organizing data from various sources, including government reports, industry databases, research studies, and relevant literature. Data on inputs (fertilizers, energy, water), outputs (yields, waste), land use, transportation, and other relevant variables were collected to create a comprehensive dataset.

3.2 HortiFootprint Category Rules (HFCR)

HFCR developed by Wageningen University & Research (Helmes et al. 2020) are a set of guidelines for calculating the environmental footprint of horticultural products. These rules cover a range of horticultural categories, including fruit and vegetables, flowers, and ornamental plants.

The HFCR are based on LCA methodology, which takes into account the environmental impacts associated with each stage of a product’s life cycle, from production to disposal. The rules cover a range of environmental impacts, including GHG emissions, energy use, water consumption, and land use.

The category rules provide detailed guidance on how to collect and analyze data for each stage of the product’s life cycle, as well as how to calculate the environmental impact of the product. They, e.g., include specific requirements for reporting the results of the analysis, i.e., transparency and completeness of the data.

The HFCR are intended to provide a standardized and transparent methodology for calculating the environmental footprint of horticultural products. They can be used by a range of stakeholders, including growers, traders, retailers, and consumers, to measure and reduce the environmental impact of horticultural products. The rules are continuously updated and improved based on new data and feedback from stakeholders, ensuring that they remain up-to-date and relevant.

3.3 Case study

Case study research is a qualitative research method that involves an in-depth investigation and analysis of a particular individual, group, event, or phenomenon. It aims to provide a comprehensive understanding of the specific case and generate detailed insights that can be applied to broader contexts. The analysis of a case study involves examining and interpreting the collected data to identify patterns, themes, and relationships. (Becker et al. 2023).

Case study (Khoshnevisan et al. 2013; Girgenti et al. 2014; Tabatabaie & Murthy 2016; Soode-Schimonsky et al. 2017) analysis was employed in this report, selecting representative strawberry production cases to analyze their carbon emissions and production methods. Primary data was collected from specific strawberry farms, including input and output flows, energy consumption, fertilizer usage, transportation, waste generation, and other relevant parameters.

3.4 Comparative analysis

Comparative analysis is a method used to identify similarities and differences between two or more objects, concepts, or phenomena. It involves examining the characteristics, features, or attributes of each item and analyzing how they relate to one another. The purpose of comparative analysis is to gain a deeper understanding of the similarities and differences in order to draw meaningful conclusions, make informed judgements, or identify patterns and trends (Walk 1998.)

In comparative analysis, various aspects of the objects being studied are compared and contrasted. This can include their structure, behavior, performance, effects, or any other relevant factors. The analysis can be qualitative, quantitative, or a combination of both, depending on the nature of the objects and the research questions or objectives (Drobnic 2014.)

Qualitative comparatiive analysis was used to compare data requirements in HFCR and studies (Khoshnevisan et al. 2013; Girgenti et al. 2014; Tabatabaie & Murthy 2016; Soode-Schimonsky et al. 2017) used in this report.

4 RESULTS

4.1 Carbon footprint studies specific to strawberries

Several carbon footprint studies have been conducted specifically for strawberries, which are one of the most widely produced and consumed horticultural crops in the world.

Soode-Schimonsky et al. (2017) aimed to assess the environmental impact of strawberry production in both Estonia and Germany. To do this, the researchers employed and LCA approach, which evaluated various environmental indicators, e.g., GHG emissions, water consumption, and land use.

The study revealed that strawberry production in Estonia had a smaller environmental footprint than in Germany. This was primarily due to Estonia’s climate, which was more suitable for strawberry production and required less water and energy inputs than Germany. Additionally, the use of pesticides and fertilizers had a significant impact on the environmental footprint of both Estonian and German strawberries.

Transportation, e.g., played a crucial role in the environmental impact of strawberry production in both countries. The study found that transportation accounted for a significant portion of the environmental footprint, particularly in the case of exporting strawberries to other countries. To mitigate this, the study recommended reducing transportation distances and promoting local consumption to minimize the environmental impact of strawberry production.

The LCA data requirements for the study included data on the cultivation of strawberries, inputs and outputs during processing, transportation, waste management, functional unit, and impact categories. Specifically, the study gathered information on the use of fertilizers, pesticides, and water during the cultivation phase of strawberry production. It, e.g., collected data on the energy and water consumption during the processing phase, i.e., washing, packaging, refrigeration. Moreover, the study included information on the transportation distances and modes used to transport strawberries from the farm to the processing plant and from the processing plant to the end consumer. The study, e.g., considered waste generated during strawberry production and processing and used 1 kg of strawberries as the functional unit to enable the comparison of the environmental impact of strawberries produced in Estonia and Germany. Finally, the study used a range of impact categories, including GHG emissions, water consumption, land use, and energy consumption, to evaluate the environmental impact of strawberry production.

Girgenti et al. (2014) studied to identify the most energy-intensive and GHG-emitting stages of the strawberry production system and suggest innovative scenarios to reduce their environmental impact.

The study discovered that the farming stage was the most energy-intensive and GHG-emitting stage, accounting for 60 - 80% of the total non-renewable energy use and GHG emissions. The use of synthetic fertilizers and pesticides during the farming stage was a significant contributor to GHG emissions and non-renewable energy use. The processing and transportation stages, e.g., had a considerable environmental impact, contributing to 10-20% of the total non-renewable energy use and GHG emissions.

The study identified several potential innovative scenarios that could lessen the environmental impact of the strawberry production system. These scenarios included utilizing organic farming methods, improving energy efficiency in processing and transportation, and promoting local consumption to reduce transportation distances. By implementing these scenarios, non-renewable energy use and GHG emissions could be reduced by up to 40-60% compared to the current strawberry production system.

Tabatabaie and Murthy (2016) used a LCA approach to evaluate the environmental impact of strawberry production in the United States from the cultivation and harvest of strawberries to their packaging for distribution to the point of first sale, known as the “farm gate”. The study aimed to identify potential areas for improvement in the environmental performance of strawberry production. The main findings of the study indicated that the farming stage was the most energy-intensive in GHG-emitting stage of strawberry production, accounting for 86% of the total energy use and 76% of the total GHG emissions. Synthetic fertilizers and pesticides used during this stage were identified as major contributors to GHG emissions and non-renewable energy use. The study, e.g., revealed that the transport of inputs and outputs had a significant impact on the environmental footprint of strawberry production, accounting for 7% of the total energy use and 8% of the total GHG emissions. However, the packaging of strawberries was found to have a relatively small environmental footprint, accounting for only 1% of the total energy use and GHG emissions. To improve the environmental performance of strawberry production, the study suggested reducing the use of synthetic fertilizers and pesticides, improving irrigation efficiency, and increasing the use of renewable energy sources. These measures could potentially reduce the energy use and GHG emissions associated with strawberry production and contribute to a more sustainable and environmentally friendly strawberry industry in the United States.

Khoshnevisan et al. 2013 aimed to evaluate and compare the environmental impacts associated with open field and greenhouse production systems for strawberries. The main findings and results of the study revealed important information about the environmental performance of both production systems.

The study found that greenhouse production required significantly higher energy inputs compared to open field production. This was mainly due to the need for heating, cooling, and lighting in the controlled environment of the greenhouse. The higher energy demand contributed to increased GHG emissions and energy-related environmental impacts.

The study provides a detailed life cycle inventory analysis (LCI) for strawberry production. The LCI phase involves collecting data on input materials, energy flows, and assumptions related to the system being studied. The data includes inputs, i.e.,machinery, labor, diesel fuel, electricity, chemical fertilizers (N, P, K, and microelements), farmyard manure, pesticides, water for irrigation, and plastic.

4.2 Analysis of the carbon footprint data for different horticulture categories

Table 1 shows comparison of data requirements between the HFCR and strawberry LCA studies (Khoshnevisan et al. 2013; Girgenti et al. 2014; Tabatabaie & Murthy 2016; Soode-Schimonsky et al. 2017) and provides valuable insights into the inclusion and exclusion of specific data requirements and the underlying reasons behind these choices. This comparison is a form of comparative analysis, where the content of the studies is analyzed to identify patterns and themes related to data requirements.

Through comparative analysis, it can be observed that certain data requirements, i.e., yield data of main products and co-products, plant input material, growing media, synthetic and mineral fertilizers, electricity, and materials use, were included in both the HFCR and strawberry LCA studies. These data requirements are considered fundamental in assessing the environmental impact of horticultural products and are thus commonly included in such studies.

On the other hand, there are specific data requirements that are present in the HFCR but not included in the strawberry LCA studies. These include historical data on area and plot use, biological pest control, and CO_2 as a fertilizer. The absence of these data requirements in the strawberry LCA studies could be attributed to several reasons.

One possible reason for the exclusion of historical data on area and plot use is that the strawberry LCA studies have focused on assessing the current or recent production practices rather than analyzing long-term historical trends. Collecting historical data on area and plot use can be challenging, requiring extensive data collection efforts and access to reliable historical records.

Similarly, the absence of data on biological pest control in the strawberry LCA studies indicate that these studies primarily focused on conventional pest control practices, i.e., synthetic pesticides, which are more commonly used in strawberry production (Bellone et al. 2023). The inclusion of biological pest control data would require specific information on the use and effectiveness of such methods, which might not have been the primary focus of the strawberry LCA studies.

Furthermore, the exclusion of data on CO_2 as a fertilizer in the strawberry LCA studies might be because CO_2 fertilization is not commonly practiced in strawberry production. The studies primarily focused on quantifying and analyzing the direct inputs and emissions associated with traditional fertilizer application methods, rather than exploring the specific impacts of CO_2 fertilization.

Table 1. Data requirement comparison between HFCR and strawberry LCA studies.

Data requirements as per HFCR (Helmes et al. 2020)	**Data requirements used in studies (Khoshnevisan et al. 2013; Girgenti et al. 2014;**

	Tabatabaie & Murthy 2016; Soode-Schimonsky et al. 2017)
Historical data on area and plot use	-
Yield data of main product and co-products	√
Crop rotation scheme data	√
Crop input material	√
Growing media	√
Capital goods in protected cultivation	√
Water	√
Crop protection active ingredients data	√
Biological pest control	-
Synthetic and mineral fertilizers	√
Organic fertilizers	√
Nitrogen and phosphorus balance	√
CO_2 as a fertilizer	-
Electricity	√
Heat	√
Fuels	√
Materials use	√
Waste	√

According to the HFCR (Helmes et al. 2020) data should be gathered on the area usage and plot history of the farm (tab 1) where the crops under study are grown, particularly if a specific LUC calculation is being conducted. If the farm has not undergone any LUC for over 20 years, this implies that there is no impact on GHG emissions due to LUC. In cases where information on land use history is not available, the latest version of the LUC tool should be used to obtain default data on LUC for the crop country combination (Blonk consultants 2017).

Main crop products refer to the primary agricultural commodities that are intentionally cultivated and harvested for consumption or commercial purposes. These are the main focus of agricultural production and typically include crops, i.e., grains, fruits, vegetables, oilseeds, and fibers.

Co-products, on the other hand, are secondary products that are produced alongside the main crop product. These can be derived from the same agricultural process or by-product streams. Co-products can have various uses and value, i.e., animal feed, bioenergy feedstock, industrial materials, or food ingredients.

The collection of yields for both main crop products and co-products is essential for assessing the productivity and sustainability of agricultural systems. These yields can be measured in terms of their physical weight or units, depending on the chosen functional unit of analysis. Additionally, it is important to gather data on the economic value of these yields, using reliable records that can be verified.

Gathering data on growing media, when cultivation uses crop rotation scheme, involves collecting information about the materials used to support plant growth and development in horticultural systems and should be documented for a minimum of three consecutive years. The information should include the area of all plots involved in the crop rotation scheme (generally equivalent to the total of the ciultivated land owned by the farmer), the annual application of organic fertilizers for each plot (measured in weight units), the crop yield per plot per year (categorized by crop type), data on the yield of green manure crops per plot annually and the total area of each plot, including its margins.

Crop input materials, i.e., seeds, seedlings, or young plants, are qualified by the number required per unit area, as well as their origin, method of transportation, and the type of packaging, container, and growing media utilized. Secondary data may be used for the production and transportation of crop input material.

To gather information on growing medium, the volume/weight, origin, and packaging should be recorded. The proportion of fossil carbon in the growing medium (based on peat constituent carbon content) should, e.g., be collected. The usage of growing media materials should be documented annually, according to the type of growing medium. If the growing medium is utilized for longer than one year, the annual usage should be determined. Additionally, if the growing media contains nutrients, data on the nutrient content, including N, carbon (C), phosphorus (P), and dry matter, should be collected. Secondary data may be employed for the production and transportation of growing medium.

The HFCR studies should take into account the greenhouse used in protected cultivation as a part of their life cycle inventory. If possible, practitioners should gather primary data. Kan and Vieira (2020) provide an overview of the required data.

To ensure proper monitoring, the use of two types of water flow must be tracked: irrigation water and other blue water. Irrigation water is dependent on the crop being grown, with the exception of green manure which is distributed evenly among all crops. There are various methods available for measuring or estimating the flow of irrigation water, and it is essential to document the method used and the source of water. To enable a more accurate nitrate emission calculation at a higher tier level, it is necessary to measure irrigation water continuously throughout the season to determine the balance of evapotranspiration and irrigation water.

It is required to collect data on the utilization of plant protection substances, i.e., herbicides, insecticides, fungicides, biocides, soil fumigants, at every stage of growing and preservation. The information must encompass the Chemical Abstracts Service (CAS) number and the specific name of the active ingredient, the application rate per area unit in grams per year or per crop weight unit for the crop being studied. The active ingredients used can be either organic or inorganic chemicals, including compounds like sulfur (S) and copper (Cu).

As there is no pre-existing data accessible on biological pest control, there is no requirement for data gathering in this area.

Regarding synthetic and mineral fertilizers, it is necessary to gather information on the application of N, P, potassium (K), calcium carbonate ($CaCO_3$), and other calcium compounds. The data for N fertilizers should be divided into urea and other N compounds. For more accurate calculations, it is preferable to collect data on the use of N, P, K compounds. The data should be in terms of weight per area for the crop being studied. Several parameters determine the impact of N fertilizer use. To use the preferred model for computing nitrate emissions arising from run-off, leaching, and ammonia emissions, additional data on the farm situation, including slope, precipitation, soil properties, and temperature, should be collected. This includes information on N compound use and the method of application. In the absence of information on which N fertilizers are used, country-specific standard values based on average N-fertilizer use can be utilized (Kool and Blonk 2020).

Organic fertilizers are made from a diverse range of sources, i.e., animal manure, by-products from the industry, and/or compost. The information that must be gathered for organic fertilizers include:

- Type of fertilizer (type of animal and whether it comes from conventional or organic farming)
- Fertilizer composition, i.e., water content, total N, organic-bound N, mineral N, P, K, cadmium (Cd), zinc (Zn), and Cu
- Transport distance

Secondary data may be utilized for the manufacturing of organic fertilizers and the elemental composition, i.e., Cd, Cu, and Zn. However, primary data must be gathered for the composition of N, P and K, the type of fertilizer and the transport distance.

N and P are essential nutrients for plant growth and are commonly supplied to crops through fertilizers. However, the excessive or inefficient use of N and P fertilizers can lead to environmental issues, i.e., water pollution, eutrophication of water bodies, and GHG emissions.

The N and P balance aims to achieve a proper equilibrium between the nutrient inputs and outputs in horticultural systems. It involves assessing the amount of N and P applied to the crops through fertilizers, irrigation water, and other sources, and comparing it to the amount of N and P taken up and utilized by plants.

The amount of plant grown per area unit must be recorded in weight units. When it comes to the refining and transportatiion of CO_2 as a fertilizer sourced from a third-party supplier, existing data may be utilized. In most situations, CO_2 is considered a waste product and therefore must be modeled accordingly. Only the necessary inputs for capturing, processing, storing, and transporting the CO_2 to the cultivation spot, i.e., greenhouse, must be taken into account. The resulting CO_2 release must be attributed to the primary process, i.e., on-site generation of heat and electricity.

The collection of electricity data must follow the general product environmental footprint (PEF) methodology (Manfredi et al. 2012). The methodology allows for the inclusion of a specific consumption mix if certain validation criteria are met. In cases where a Combined Heat and Power (CHP) system supplies electricity to a greenhouse owned by the same party, the electricity flows may be determined by calculating the CHP’s effectiveness and external electricity exports i.e., to the grid.

To assess the impact of heat, the amount of energy used per hectare must be recorded. If the heat is generated from a CHP located on a farm, whether it belongs to the same owner or a neighboring farm, primary data provided by suppliers may be used. The heat flow from a CHP to a greenhouse owned by the same party can be determined by calculating the CHP’s effectiveness and external heat exports. If the heat comes from sources other than a CHP, existing data may be used.

To assess the fuel use, information on the following aspects per area unit shall be collected: the type of fuel, the energy content of the fuel specified in either higher heating value (HHV) or lower heating value (LHV), the fuel mix including proportional distribution of renewable fuels, the weight and energy content of the unit, and the source or origin of the fuel.

The use of substrate material as a growth medium refers to the practice of utilizing specific materials to provide a suitable environment for plant growth. Substrates, e.g., growth mediums or growing media, are materials that support plant roots, provide vital nutrients, and facilitate water and nutrient uptake, i.e., containers for pot soil.

Substrate materials can vary depending on the specific needs of the plants being cultivated. Common examples of substrate materials include peat moss, perlite, vermiculite, rockwool, mulch and various types of compost. These materials are selected based on their physical properties, i.e., water-holding capacity, aeration, and nutrient availability.

All inputs utilized, including those that come with the saplings and those included at a later stage, should be recorded in weight units per hectare and per product. In addition, materials used for soil mulching, both natural, e.g., mulch, straw, and synthetic, e.g., plastics, may be applicable for open air and greenhouse cultivation systems. Materials used for guiding and supporting plants, e.g., wood, steel, plastics, should be recorded. Plant lifting aids, i.e., those used for potted plants and substrate systems like strawberries, should be included. Quantities of all materials used should be documented in weight units per year per hectare and per unit of product if necessary for calculations. The following information should be documented: material type, production source, percentage of recycled content, and waste management method.

Quantification of organic farm waste is not necessary as the quantities are usually not excessive. Farm waste comprises plant and crop residues, as well as discarded materials.

In summary, the comparartive analysis of Table 1 highlights the inclusion and exclusion of specific data requirements in the HFCR and strawberry LCA studies. It suggests that the choice of data requirements in the strawberry studies was influenced by the scope, objectives, and practical considerations of each study. The comparative analysis provides valuable insights into the reasons behind these choices and helps identify potential areas for further research and data collection to enhance the comprehensiveness of future LCA models for horticultural products.

4.3 Data requirement themes to model carbon emission of strawberry

Based on the findings of R1, several data requirement themes can be identified for modeling the carbon emissions of strawberries. These themes include:

a) Yield and production data: Accurate information on strawberry yields, including main products and co-products, is essential for estimating the carbon emissions associated with production. Yield data provides insights into resource inputs, i.e., fertilizers and energy, and helps quantify the emissions generated per unit of yield.
b) Input materials and growing medium: Understanding the composition and usage of crop input materials and growing media in strawberry production is crucial for assessing their carbon footprint. This includes data on fertilizers, irrigation water, plant protection products, and substrate materials.
c) Energy consumption: Data on electricity, heat, and fuels used in various stages of strawberry production, including cultivation, processing, and transportation, are necessary to estimate the carbon emissions associated with energy consumption.
d) Waste management: Information on waste generated during strawberry production, i.e., agricultural residues or packaging waste, is relevant for calculating the carbon emissions attributed to waste disposal.

e) Specific emissions factors: Quantifying the emissions factors associated with specific activities, i.e., fertilizer application, energy use, or waste management, enables more accurate estimation of carbon emissions.

To model the carbon emissions of strawberries using the findings of R1, these data requirement themes need to be considered and incorporated into the LCA model. Collecting comprehensive and reliable data within these themes will contribute to a more robust and accurate assessment of the carbon footprint of strawberries.

4.4 Presentation of the proposed standard carbon footprint model for strawberries

The standard carbon footprint model for strawberries could be developed and would enable the comparison of the environmental impact of strawberries produced in different regions and under different scenarios and could contribute to efforts to reduce the environmental footprint of food production.

Table 2 shows different categories of horticultural products that could be included in a LCA model. Each row of the table represents a category of horticultural product, and the columns indicate the category name and some examples of products that fall within that category.

I.e., the “Fruits” category includes a range of fruits, e.g., berries, citrus, stone fruits, pome fruits, and tropical fruits. The “Vegetables” category includes leafy greens, root vegetables, cruciferous vegetables, and nightshade vegetables. The “Herbs and spices” category includes herbs and spices, e.g., basil, mint, oregano, thyme, and cinnamon.

Table 2. Suggested plant categories for the proposed LCA model.

Category	Examples
Fruits	Berries, citrus, stone fruits, pome fruits, tropical fruits
Vegetables	Leafy greens, root vegetables, cruciferous vegetables, nightshade vegetables

Herbs and spices	Basil, mint, oregano, thyme, cinnamon
Nuts	Almonds, walnuts, pistachios
Ornamentals	Cut flowers, ferns, ivy
Grains	Wheat, rice, oats
Medicinal plants	Echinacea, ginseng, St.John’s wort
Edible mushrooms	Shiitake, portobello, oyster mushrooms
Beverage crops	Coffee, tea, wine

Similarly, the “Nuts” category includes tree nuts, i.e., almonds, walnuts, and pistachios, while the “Ornamentals” category includes cut flowers, ferns, ivy. The “Grains” category includes cereal crops, i.e., wheat, rice, and oats. The “Medicinal plants” category includes plants used for medicinal purposes, i.e., echinacea, ginseng, and St. John’s wort. The “Edible mushrooms” category includes a variety of mushrooms, i.e., shiitake, portobello, and oyster mushrooms. Finally, the “Beverage crops” category includes crops used to make beverages, i.e., coffee, tea, and wine.

The table serves as a quick reference guide to the different horticultural categories that could be included in a LCA model. However, the model would need to be continuously updated to include more categories and crops.

Within the “Fruits” category, subcategories can be created for different types of berries (strawberries, blueberries, raspberries, etc.), and within the “Vegetables” category, subcategories can be created for different types of leafy greens (spinach, lettuce, kale, etc.), providing a more detailed breakdown of horticultural products.

Horticultural products can have regional variations in cultivation practices, inputs, and environmental impacts (Soode-Schimonsky et al. 2017). Incorporating regional data and variations within the model can enhance its accuracy and relevance, e.g., different regions may have different growing conditions or pest management strategies that impact the environmental performance of horticultural products.

Beyond the cultivation stage, the LCA model can, e.g., consider the post-harvest and processing stages of horticultural products. This can include activities as storage, packaging, transportation, and processing into value-added products like juices, jams, or frozen produce. These stages can have significant environmental impacts that should be accounted for in the model.

In addition to carbon footprint assessment, incorporating a water footprint assessment can provide insights into the water consumption and potential impacts associated with horticultural products. This can be particularly relevant given the increasing concerns over water scarcity and sustainable water management in agricultural systems.

While the focus of the LCA model is primarily on environmental impacts, considering social and economic aspects can provide a more comprehensive assessment. This can include factors, i.e., labor conditions, fair trade practices, socioeconomic benefits to local communities, and the overall economic sustainability of horticultural production.

While GHG emissions are a critical factor in assessing environmental impact, expanding the model to include other categories, i.e., land use, water pollution, biodiversity loss, and soil degradation can provide a more holistic understanding of the sustainability of horticultural products.

5 DISCUSSION

5.1 Comparison of the proposed model with existing models

There are a few existing carbon footprint models for horticultural products that the proposed model could be compared to. One widely used model is the One-Click LCA software, which has built-in database of environmental data for a range of building materials, products, and processes, including horticultural products. The software uses LCA approach to calculate the carbon footprint and other environmental impacts of different products and processes.

Compared to One-Click LCA, the proposed model would be more specific to horticultural products and would have a greater focus on factors that are specific to the horticultural industry, i.e., crop inputs, cultivation practices, supply chain characteristics. Additionally, the proposed model could be tailored to individual horticultural categories (tab 2), whereas One-Click LCA provides a more general approach.

Another carbon footprint model that could be compared to the proposed model is the Cool Farm Tool, which is designed specifically for agriculture and horticulture products. The Cool Farm Tool uses a combination of LCA and carbon accounting methodologies to calculate the carbon footprint and other environmental impacts of different crops, taking into account factors, i.e., land use, crop inputs, and energy use.

Compared to the Cool Farm Tool, the proposed model would likely be more tailored to horticultural products specifically and could potentially have a greater focus on factors, i.e., transportation and distribution, end-of-life options, and the impact of different growing systems. Additionally, the proposed model could potentially be more comprehensive in terms of the range of horticultural categories and crops that it covers.

It is worth noting that the proposed model could, e.g., be complementary to existing models, e.g., One-Click LCA, Cool Farm Tool, rather than being seen as a direct competitor. Depending on the specific needs of different stakeholders, different models may be more appropriate for different applications. Therefore, having a range of models available could be beneficial in providing a deeper and nuanced comprehesion of the environmental impacts of horticultural products.

5.2 Implications of the proposed model for the horticulture industry

Implementing a standard carbon footprint model for horticulture can have several potential implications, both positive and negative.

By using a standardized carbon footprint model, horticulture producers can identify areas where they can reduce their GHG emissions, leading to a more environmentally sustainable production process. A standardized carbon footprint model can help to increase consumer awareness about the environmental impact of horticulture products, leading to greater demand for environmentally responsible products, which in turn may allow producers to have a competitive advantage over those who do not adopt more environmentally responsible production practices, as consumers increasingly prioritize sustainability in their purchasing decisions.

However, there may be potential negative implications of implementing a standard carbon footprint model, e.g., increased production costs, differential impacts on small-scale producers, limited effectiveness. Implementing a standardized carbon footprint model may require additional resources and expertise, which can increase production costs for some producers. Small-scale horticulture producers may be disproportionately affected by the implementation of a standardized carbon footprint model, as they may lack the resources and expertise to implement more environmentally responsible practices. A standardized carbon footprint model may not be effective in all contexts, as there may be significant variation in production practices and environmental impacts across different regions and horticulture categories.

To manage these potential implications, it will be important to ensure that the transition to a more environmentally responsible production process is sustainable and equitable.

Efforts should be made to provide resources and support to small-scale horticulture producers to help them adopt more environmentally responsible practices. Governments and other stakeholders can provide incentives for horticulture producers, i.e., financial incentives or certification programs. Collaboration among stakeholders, including producers, retailers, and researchers, can help to share knowledge and resources to support the adoption of more sustainable practices. The standardized carbon footprint model should be continuously refined and updated based on new data and feedback from stakeholders, to ensure that it remains effective and relevant over time.

5.3 Limitations of the study and areas for future research

The development of a comprehensive LCA model for all horticultural products would provide valuable insights into the environmental impacts of horticultural production systems. However, there are several challenges and limitations that need to be addressed.

One significant challenge is data availability. Collecting and analyzing data on the inputs and outputs of horticultural production systems can be difficult, especially for small-scale producers or in regions with limited resources. The accuracy and reliability of the LCA model would depend heavily on the quality and completeness of the data collected. Therefore, improving the quality and availability of data on horticultural production systems is essential.

Another challenge is the variability of production systems. Horticultural production systems can vary significantly depending on factors, i.e., crop type, geography, climate, and production scale (Girgenti et al. 2014, 48-53, 473 - 474; Soode et al. 2015, 168 - 179; Tabatabaie & Murthy 2016, 548 - 554; Soode-Schimonsky et al. 2017, 564 - 577; Perez-Neira & Grollmus-Venegas 2018, 60-68; Ronga et al. 2019, 836 - 845; Valiante et al. 2019 249 - 261; De Jesus Pereira et al. 2021, 282; Helmes et al. 2021; Parajuli et al. 2022.) Creating a LCA model that accounts for this variability would be complex and resource intensive.

The complexity of supply chain is another challenge. Horticultural products often go through complex supply chains involving multiple stages, from production to retail. Accounting for the environmental impacts of each stage of the supply chain would require detailed data on the inputs and outputs of each stage.

Moreover, the impact assessment methods used in LCA have limitations, including the potential for subjective judgements, the difficulty of comparing impacts across different environmental categories, and the challenge of accounting for cumulative impacts. Interpreting the results of a LCA model can be challenging, as the impacts of different environmental categories may be difficult to compare. Additionally, stakeholders may have different priorities or perspectives on what constitutes a significant impact.

Developing a comprehensive LCA model for all horticultural products would require significant resources and time, from data collection to interpretation and reporting. This could be a significant barrier to adoption by small-scale producers or organizations with limited resources.

Despite these challenges, LCA can be a valuable tool for identifying opportunities to reduce the environmental impact of horticultural production systems and promote more sustainable practices. There are several areas of research that could help advance the use of LCA in the horticultural industry and improve our understanding of the environmental impacts of horticultural production systems.

One potential area of research is data quality and availability. Improving the quality and availability of data on the inputs and outputs of horticultural production systems would help to improve the accuracy and reliability of LCA models. Research could focus on developing more efficient data collection methods or improving the consistency and comparability of data across different regions and production systems.

Another area of research is impact assessment methods. Developing new or improved impact assessment methods could help to address some of the limitations and challenges associated with existing methods, e.g., research could focus on developing impact assessment methods that better account for cumulative impacts or that can be more easily applied to complex supply chains.

Accounting for geographic variability in horticultural production systems would help to create more accurate and representative LCA models. Research could focus on developing regional LCA models or on identifying factors that contribute to variability in environmental impacts across different regions.

Moreover, incorporating social and economic impacts into LCA models could provide a more comprehensive picture of the sustainability of horticultural production systems. Research could focus on developing methods for incorporating social and economic impacts into LCA models or on identifying the most relevant social and economic impacts to consider.

Finally, the horticultural industry generates significant amounts of waste and has the potential to contribute to a circular economy through practices, i.e., composting or recycling. Research could focus on developing LCA models that account for the environmental impacts of waste management practices or on identifying strategies for improving waste management in the horticultural industry.

Despite the challenges and limitations associated with developing a comprehensive LCA model for all horticultural products, the potential benefits of using LCA to promote more sustainable production practices are significant. Ongoing research in areas, i.e., data quality and availability, impact assessment methods, geographic variability, social and economic impacts, and waste management can help to overcome these challenges and advance the use of LCA in the horticultural industry. With a more comprehensive understanding of the environmental impacts of horticultural production systems, stakeholders can make informed decisions that promote sustainability and protect the environment for future generations.

Artificial intelligence (AI) can play a crucial role in expediting the making of an LCA model for horticultural products. AI can automate the data collection process, making it more efficient and reducing the need for manual data entry. Machine learning algorithms can be used to extract information from large databases or sensor data, making it easier to obtain the necessary data for the LCA analysis.

AI can automate the analysis of data, making it easier to identify patterns and trends. Clustering algorithms can be used to group similar horticultural products, while decision trees can be used to identify the most significant factors affecting the environmental impact of a product. This can help to prioritize areas for improvement and focus on reducing the most significant sources of environmental impact.

AI can build predictive models that estimate the environmental impact of horticultural products based on their characteristics. Regression algorithms can be used to model the relationship between the use of fertilizers and the carbon footprint of a crop. These models can help to evaluate the impact of different scenarios and identify the most effective strategies for reducing the environmental impact of horticultural products.

AI can optimize the LCA model by identifying the most significant variables and parameters. Genetic algorithms can be used to optimize the use of water and energy in the production of horticultural products, reducing the environmental impact of these resources.

Finally, AI can generate reports and visualizations that communicate the results of the LCA analysis more effectively. Natural language processing algorithms can be used to generate summaries of the main findings of the analysis, while data visualization tools can be used to create interactive graphs and charts. This can help to communicate the results of the analysis to a wider audience and facilitate decision-making.

6 CONCLUSION

Developing a standard carbon footprint model for the horticulture industry can help to promote more sustainable and environmentally responsible production practices. By providing a standardized approach for calculating and reporting GHG emissions from different horticulture categories, this model can help to increase transparency and accountability throughout the supply chain, while, e.g., enabling stakeholders to identify opportunities for reducing their carbon footprint.

However, the adoption and implementation of a standard carbon footprint model will require addressing a number of potential barriers, including the need to ensure that the model meets the specific needs and requirements of different stakeholders in the industry.

To address these challenges, it will be important to engage with stakeholders throughout the development and implementation process, and to provide training and support to help stakeholders understand and implement the model effectively. It will be important to manage the potential implications of implementing the model, e.g., potential changes to supply chain dynamics and the need to ensure that the transition to more environmentally responsible production practices is sustainable and equitable.

In conclusion, the comparison of the carbon emission footprint of strawberries with the HFCR provides valuable insights into the environmental impact assessment of horticultural products. The analysis of data requirements and their inclusion or exclusion in the studies reveals important considerations for modeling carbon emissions in strawberry production. The research questions addressed in this study shed light on the carbon footprint of strawberries and the data requirements needed to model their emissions accurately.

The comparison between the carbon emission footprint of strawberries and the HFCR highlights both similarities and differences. While the specific data requirements for strawberry LCA studies may not align perfectly with the HFCR, elements are overlapping. Data requirements, i.e., yield data, plant input material, growing media, synthetic and mineral fertilizers, electricity, and materials use are common to both strawberry LCA studies and the HFCR. This indicates that the carbon emissions associated with these factors are considered significant and relevant in assessing the environmental impact of strawberries according to the HFCR.

However, there are certain data requirements, including historical data on area and plot use, biological pest control, and CO_2 as a fertilizer, that are included in the HFCR but not specifically addressed in the strawberry LCA studies. The exclusion of these data requirements in the strawberry studies suggests that their focus might have been on other aspects of the carbon footprint assessment, i.e., direct inputs and emissions, rather than long-term historical trends or specific practices like biological pest control or CO_2 fertilization.

The comparison of strawberry carbon emissions with the HFCR highlights the importance of specific data requirements in evaluating the environmental footprint of horticultural products. The identified data requirement themes provide guidance for modelling the carbon emissions of strawberries, enabling a more comprehensive evaluation of their environmental footprint.

Overall, developing and implementing a standard carbon footprint model for the horticulture industry has the potential to play a significant role in mitigating climate change and promote sustainable development.

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