# Sustainable Production and Consumption
## Life Cycle Assessment of organic chocolate production in Peru
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| **Corresponding Author:** | Ian Vázquez-Rowe<br>Pontifical Catholic University of Peru<br>PERU |
| **First Author:** | Ian Vázquez-Rowe |
| **Order of Authors:** | Ian Vázquez-Rowe |
| | Patricia Mogrovejo |
| | Eizo Muñoz, MSc Civil Engineering |
| | Pablo González Socorro |
| | Karin Bartl |
| | Isabel Quispe, PhD Environmental Science |
| | Jhonnatan Murga |
| | Shenali Madhanaroopan |
| | Salma Fotovat |
| | Taylor Stanley |
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Lima, Peru

March 26th 2025

Dear editor,

We are presenting an original research manuscript in which we analyse the production of organic cocoa in Peru to produce a set of three organic chocolate products, which are then exported to Canada. Cocoa production in Latin America is thriving thanks to competitive international prices, but there is an important lack of environmental assessment studies that analyze the environmental profile of this commodity. Therefore, in our study we have analyzed the production of dried organic cocoa beans in a region in central Peru, as well as the delivery of these beans to a manufacturing company in coastal Peru, where the chocolate products are produced and exported all over the world, although the three products assessed in this case are exported to Canada.

We consider that our study is novel as it presents the first full LCA study in scientific literature that covers the full production of chocolate products manufactured in the Global South, rather than being exported as dried beans to Europe or the US. Moreover, we have identified that prior studies underrepresent certain activities in the production of cocoa beans, such as GHG emissions derived from cocoa pod husk management or fermentation of the cocoa beans. Similarly, previous studies lacked a full computation of the biogenic carbon cycle, whereas we have modelled all carbon emission and storage processes that occur in the cultivation systems.

In this context, we present a research paper entitled *Life Cycle Assessment of organic chocolate production in Peru*, by Ian Vázquez-Rowe, Patricia Mogrovejo, Eizo Muñoz-Sovero, Pablo González Socorro, Karin Bartl, Isabel Quispe, Jhonnatan Murga, Shenali Madhanaroopan, Salma Fotovat, and Taylor Stanely, which hopefully will be published in *Sustainable Production and Consumption*. We have screened and selected the most suitable data and discussion to include in the study. We state that our manuscript has not been previously published, and is not under consideration by any other scientific journal. Additionally, all authors are aware of, and accept responsibility for the contents included in the manuscript.

Yours sincerely,

Ian Vázquez-Rowe and co-authors

# Life Cycle Assessment of organic chocolate production in Peru

Ian Vázquez-Rowe[1], Patricia Mogrovejo[1], Eizo Muñoz[1], Pablo González Socorro[2], Jhonnatan Murga[3], Shenali Madhanaroopan[4], Salma Fotovat[4], Taylor Stanley[4], Karin Bartl[1], Isabel Quispe[1]

[1] Peruvian Life Cycle Assessment & Industrial Ecology Network (PELCAN), Department of Engineering, Pontificia Universidad Católica del Perú (PUCP), Avenida Universitaria 1801, San Miguel 15088, Lima, Peru

[2] Departamento de Economía y Estadística, Facultad de Ciencias Económicas y Empresariales, Universidad de León, León, Spain

[3] Machu Picchu Foods, Avenida Cádiz 206, San Isidro 15076, Lima, Peru

[4] Sustainability, Riverside Natural Foods Ltd., Concord, Ontario, Canada

* Corresponding author. E-mail: ian.vazquez@pucp.edu.pe

## Abstract

Life Cycle Assessment (LCA) studies on Agroforestry systems in Latin America are not as common as in other agri-food sectors justifying the need to obtain more data and results in these types of systems. The current study focuses on providing a cradle-to-gate LCA of the production of a set of organic chocolate products in Peru, considering the cocoa cultivation practices of a group of 21 female producers located in central Peru. Beyond fossil and biogenic emissions linked to cultivation management activities, transport of dried cocoa to the processing plant, and manufacturing activities at the chocolate producing plant, carbon capture on fields by cocoa and shading trees was modeled and included in the carbon balance. A total of 8 impact categories were selected in the assessment, considering different environmental compartments. Results for global warming using the main scenario show a range of values from 4.33 kg $CO_2$eq per kilogram of final chocolate product to 4.88 kg $CO_2$eq. Most impacts are derived from the production of dry cocoa beans and, to a lesser extent, upstream sugarcane production. However, important differences in global warming impacts were evident when the different cocoa producers were analyzed, with agroforestry systems presenting significantly lower greenhouse (GHG) emissions than cocoa monocrops. In terms of water scarcity, the activities at the chocolate processing plant were found to contribute more than water use at the cocoa cultivation sites. For other impact categories, toxicity emissions at the cultivation site were low given the organic characteristics of the fields, which do not use conventional pesticides to combat pests. The post-harvest management of the cocoa pods (i.e., composting) appears to be a critical source of GHG emissions. Hence, adequate composting conditions maintain the emissions of methane at low levels, but direct return of the pods to the field can generate a two- or three-fold increase in GHG emissions. Carbon sequestration from above ground biomass, mainly from shading trees and cocoa trees, appears to mitigate an important fraction of these emissions as long as shading is homogeneous and sufficiently dense across the cocoa-producing fields.

**Keywords:** agroforestry; climate change; cocoa; environmental impacts; industrial ecology; water footprint.

## Declaration of competing interest

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

The study has been mostly funded by Riverside Natural Foods Ltd., a food manufacturing company specializing in natural and organic snacks. However, the authors declare that neither these nor any other interests have directly or indirectly influenced the objectivity of this paper, and the findings and conclusions in the paper are those of the authors alone, independent of their organizations or funding sources.

## Data availability

Data will be made available on request.

## Credit author statement

**Ian Vázquez-Rowe:** conceptualization, investigation, validation, resources, writing (original draft), supervision, funding acquisition, project administration; **Patricia Mogrovejo:** methodology, validation, formal analysis, investigation, writing (original draft); **Eizo Muñoz:** methodology, formal analysis, investigation, software; **Pablo González-Socorro:** methodology, formal analysis, writing (review and editing); **Karin Bartl:** methodology, formal analysis, writing (review and editing); **Isabel Quispe:** conceptualization, formal analysis, writing (review and editing), supervision, funding acquisition; **Jhonnatan Murga:** validation, supervision; **Shenali Madhanaroopan:** supervision, writing (review and editing); **Salma Fotovat:** validation, supervision, funding acquisition; **Taylor Stanley:** conceptualization, supervision, funding acquisition, writing (review and editing).


## Acknowledgements

The authors thank the 21 farmers from the Nuwa Muun project for sharing their knowledge and data, as well as the technical personnel of Machu Picchu Foods for their time collecting the necessary primary data for the study.

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[1] Peruvian Life Cycle Assessment & Industrial Ecology Network (PELCAN), Department of Engineering, Pontificia Universidad Católica del Perú (PUCP), Avenida Universitaria 1801, San Miguel 15088, Lima, Peru

[2] Departamento de Economía y Estadística, Facultad de Ciencias Económicas y Empresariales, Universidad de León, León, Spain

[3] Machu Picchu Foods, Avenida Cádiz 206, San Isidro 15076, Lima, Peru

[4] Sustainability, Riverside Natural Foods Ltd., Concord, Ontario, Canada

* Corresponding author. E-mail: ian.vazquez@pucp.edu.pe

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of the cocoa pods (i.e., composting) appears to be a critical source of GHG emissions. Hence, adequate composting conditions maintain the emissions of methane at low levels, but direct return of the pods to the field can generate a two- or three-fold increase in GHG emissions. Carbon sequestration from above ground biomass, mainly from shading trees and cocoa trees, appears to mitigate an important fraction of these emissions as long as shading is homogeneous and sufficiently dense across the cocoa-producing fields.

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## 1. Introduction

Agri-food production is an important sector worldwide given its key role in supplying humans with food. Its preservation is critical in providing human communities with food safety (Fung et al., 2018) and security (Liverman and Kapadia, 2012). However, the production of food to feed over 8 billion people on Earth is not exempt from important environmental impacts due to the stress that massive production produces (Clark et al., 2019). For instance, approximately 30% of anthropogenic greenhouse gas (GHG) emissions are linked to the production of direct or indirect human consumption of food (Crippa et al., 2021), although this percentage is variable depending on the assumptions that are considered and how land use changes (LUCs) are computed. Nevertheless, climate change is only one of the planetary boundaries in which food production has an important role (Röckstrom et al., 2020).

Agricultural, agroforestry and aquaculture systems, for instance, are highly responsible for the current scarcity of nutrients, which compromises their biogeochemical cycles, but can also generate important eutrophication emissions to freshwater and marine water bodies (Le Moal et al., 2019). Water is also an important resource in terrestrial food systems, and its scarcity, similarly to nutrients, can act as a limiting factor for food production development (Dinar et al., 2019). In fact, agriculture is the main source of human consumption of water, and the uneven distribution of this resource can negatively impact ecosystems and human communities.

The uneven distribution of water is particularly evident in certain Latin American nations, such as Peru, where an important part of the population lives along the hyper-arid coastal strip (Sánchez-Matos et al., 2024). In contrast, agroforestry systems, like cocoa and coffee are produced in areas where rainfall and surface water resources are relatively plentiful, although these general conditions may change through time due to the semi-cyclic effects of El Niño-Southern Oscillation and the gradual impacts that climate change is exerting on water resources across the world (Boeckx et al., 2020).

Considering that agri-food production is both a cause and is affected by multiple environmental impacts, Life Cycle Assessment (LCA) has been identified as a useful and commonly applied environmental management methodology in food systems to determine their environmental profile and, ultimately, estimate the damage that this profile can cause on human health, ecosystems or resource depletion (McLaren et al., 2021). LCA, which is standardized by the ISO 14040 and 14044 standards, extracts the material and energy flows of different systems and links these to different categories of environmental impacts and damage, in what are named impact categories (ISO, 2006a, b).

The use of LCA in agri-food systems was initiated in the late 1990s, and has ever since gained increasing attention, with the development of an ever-growing number of inventory flows that mathematically describe a wide range of different agricultural, fishing, aquaculture or livestock products (McLaren et al., 2021). In recent years, thanks to a more widespread application of agri-food product LCA studies, new studies have been conducted analyzing the environmental profile of human diets across the world (Ritchie et al., 2018; Jolliet et al., 2022), in which most of the focus was linked to: i) identifying the food products and groups with the highest environmental impacts; ii) comparing different types of human diets (e.g., meat-based, vegetarian, vegan…); or, iii) optimizing current diets in order to combine healthy and sustainable parameters with the objective of attaining balanced diets (Falcone et al., 2020; Larrea-Gallegos and Vázquez-Rowe, 2020). Most of these studies have focused mainly on GHG emissions (Sugimoto et al., 2021) and the Global North, but some have also delved into other environmental aspects, such as water scarcity (Zucchinelli et al., 2021), or other areas of the world, such as South America (Vázquez-Rowe et al., 2017; Gutiérrez et al., 2023).

Despite this surge in reporting the environmental profile of agri-food products worldwide, agroforestry products, such as coffee, Brazil nut or cocoa, however, have been intermittently reported in the LCA scientific literature. Although there is increasing literature on the matter, which is described below, studies are not as common as in other sectors, justifying the need to obtain more data and results in these types of systems. Hence, the main objective of the study was to carry out a cradle-to-gate LCA of a set of three organic chocolate products produced by a chocolate manufacturing company in Peru based on the organic cocoa beans cultivated by a group of 21 female producers in the vicinity of the city of Satipo, in Junín, central Peru. The sample of producers considers a range of three different production systems, including agroforestry, intercropping and monocropping. In fact, we consider that the main novelty of the study is related to it being the first LCA study developed in Peru that considers different cultivation production systems for organic cocoa at a national level and expands the system boundary to the manufacturing of local-produced chocolate products. The target audience of the study is expected to be LCA practitioners that work with agroforestry products, as well as stakeholders in the cocoa and chocolate sectors interested in analyzing the environmental impacts derived from their activities.

## 2. Literature review

In terms of cocoa production, Utomo and colleagues (2016) conduct an environmental assessment of *Criollo* cocoa production in cocoa-coconut and cocoa-rubber monocultures (i.e., cocoa-rubber) and agroforestry (i.e., cocoa-coconut) systems in Indonesia. The study determined that the cocoa-coconut agroforestry system has lower environmental impacts compared to monoculture in the three categories analyzed: 48% lower in global warming - GW (36.7 kg $CO_2$eq/t), 47% in acidification and 38% in eutrophication. The environmental hotspots identified were the production and use of fertilizers and pesticides in crops, being greater in monocultures of *Criollo* cocoa since it is not resistant to pests and, therefore, requires careful treatment for the correct growth of the pod, increasing the use of agrochemicals (Utomo et al. 2016).

In the case of Latin America, studies carried out mainly in Ecuador, Brazil and Colombia are reported. Hernandes and colleagues (2022), on the one hand, analyzed cocoa production in the Brazilian state of Pará, where the harvest, fermentation and drying phases were studied. According to their analysis, applying composting, such as peel waste, and eliminating nitrogen-rich fertilizers can reduce emissions by up to 80% (Hernandes et al. 2022). On the other hand, Ortiz-Rodriguez and colleagues (2016) in Colombia estimated the carbon footprint of cocoa beans in traditional and agroforestry production systems. The emissions generated by both systems were of a similar order of magnitude, where the conventional system generated 8 kg $CO_2$eq/kg, with the production phase being the most polluting (i.e., 86% of total GHG emissions). In the case of the agroforestry system, emissions increased to 8.89 kg $CO_2$eq/kg and the production phase remained the most polluting at 96% of total emissions (Ortiz-Rodriguez et al. 2016). Despite a better cocoa yield from agroforestry (1200-1500 kg/ha) in comparison with conventional (400-500 kg/ha), the agroforestry system requires specific NPK fertilizers and pesticides in the production phase that contribute mainly to the slightly higher impacts.

In Ecuador Perez-Neira (2016) estimated the energy sustainability of exported cocoa, in which the functional unit (FU) was set at 1 kg of 100% cocoa chocolate ready for sale. Although this approach was based on energy consumption, it also estimated GHG emissions and compared them in two farming systems: traditional and mechanized, yet no air emissions were accounted for from the degradation of cocoa pods or the fermentation of the mucilage. While in the traditional system most emissions come from fertilizers (49%), in the case of the technical system, petroleum derivatives were the main emitters (30%). Despite the change in the distribution of emissions in the traditional and technical system, the final values of $CO_2$eq are similar, being 2.57 and 2.82 per kg $CO_2$eq/FU, respectively. Furthermore, the higher yield in modernized farms is not necessarily favorable in terms of environmental impacts due to the increase in irrigation and use of fertilizers, which may lead to a lower energy efficiency ratio than in traditional farms (Perez-Neira 2016).

Also in Ecuador, a recent study by Avadí (2023) performs an environmental assessment using LCA-based statistics. The entire value chain of fine and aroma cocoa is covered from its cultivation to its export and subsequent distribution to the Ecuadorian market and other countries. Most of the cocoa was produced by small farmers, who had an impact on climate change of 2.65 kg $CO_2$eq/kg produced from organic beans and 4.04 kg $CO_2$eq/kg produced from commodity beans. The main recommendation of the study was to improve efforts and initiatives to enhance environmental performance, e.g., by enhancing cultivation infrastructure, promoting agroforestry and consolidating production “clusters” according to good field or manufacturing practices. Regarding medium and large producers, GHG emissions were higher (4.53 kg $CO_2$eq/kg produced) in the case of large producers but lower in the case of medium producers (1.84 kg $CO_2$eq/kg produced). Avadí (2023) hypothesizes that this could be due to the different agricultural practices in each field such as the intensity of water use, energy, transportation, or fertilization and pesticide use. Finally, the main conclusion reached is that the environmental burden in climate change of Ecuadorian cocoa is much lower compared to the production chains of other countries such as Ghana, Indonesia, or Brazil (Avadí, 2023). The author suggests that the main reason was due to the fundamental role played by LUCs. While in countries like

Ivory Coast more than 90% of environmental impacts are due to land use and/or land cover change, in Ecuador it only reaches ca. 20%. This is because in Ecuador cocoa plots sampled had been planted for more than 20 years in areas with high vegetation, unlike the Ivory Coast, making carbon sequestration high and making the impacts on climate change low or negative (Avadí, 2023).

In Peru, Raschio and colleagues (2017) published a study in which a set of ca. 1900 farms in the province of Tocache, region of San Martin, were assessed to test the probability of farms to expand their agricultural frontier based on whether they were located in high or low GHG emission hotspots. Data for these farms were modeled for years 2008-2010. The life cycle modelling was then combined with geo-information systems (i.e., GIS) and geostatistics to identify high and low risk areas for initial and subsequent deforestation. The system boundaries only included cultivation up to the preparation of cocoa beans prior to fermentation but included LUCs based on primary data. The use of the GIS tool allowed the producers to be grouped according to their level of GHG emissions, obtaining spatial data regarding deforestation dynamics. Likewise, it was evident that the application of regional averages represents a limitation for perennial crops at the local level, underestimating up to 400% in the GHG levels obtained for the area under study (Raschio et al. 2017).

Recanati et al. (2018) also modeled their LCA environmental impacts of a chocolate bar produced in Italy, using cocoa liquor obtained from Peruvian cocoa beans as the main ingredient (i.e., 50.1%). Interestingly, other cocoa-based ingredients, such as cocoa butter and powder, were obtained from cocoa beans from unspecified geographical origins. The inventory data from Peruvian cocoa production in this case was from the years 2014 and 2015. The results that they computed suggest that the cultivation stage represents about 60% of total environmental impacts in terms of global warming, but are higher for categories such as acidification, eutrophication and abiotic depletion. However, it is mainly the other cocoa ingredients from unspecified origins that represented a wider part of the impacts, whereas Peruvian cocoa liquor showed much lower environmental impacts, despite representing more weight per functional unit (FU). This divergence between Peruvian and unspecified cocoa production is explained by the authors based on different cultivation systems and different levels of data quality. On the one hand, the Italian company producing cocoa provided high-quality data from Peruvian cultivation sites, which were mainly mature plantations (over 10 years) in agroforestry systems with no chemical addition and abundant shading trees. On the other hand, the remaining cocoa products with unspecified origin were modeled using secondary data from the ecoinvent database, which provides more generic and conservative global elementary flows.

Based on the literature review above, we consider that the number of studies on the environmental profile of cocoa production and derived products is scarce, especially in a country like Peru in which its production is spread out across an important portion of its territory. Furthermore, studies on organic production are also limited or their assessment as compared to conventional production systems is not fully discussed. Finally, full accountability of the biogenic carbon cycle, considering the full range of biogenic carbon emissions and capture, is lacking. Therefore, as mentioned above, the aim of the current study is to fulfill some of these gaps in the scientific literature and provide a full LCA describing the environmental impacts related to the production of organic chocolate products in Peru.

## 3. Materials and Methods

### *3.1 Description of the production system*

The current study focuses on analyzing the environmental profile of organic cocoa beans production and their subsequent transformation into organic chocolate products. For this, a set of 21 female producers which took part in the Nuwa Ruun project, all located in the vicinity of the city of Satipo (11°15′15″S; 74°38′12″W), province of Satipo, region of Junín, were sampled. All producers deliver their cocoa beans to the regional distribution center in Satipo for Machu Picchu Foods (MPF). The cultivation system in all cases was organic, although the production system varied, with 2 producers having an agroforestry system, 5 producers presented a monocrop production system, and the remaining producers (i.e., 14) an intercrop system with other fruit trees (e.g., oranges). On average, the density of cocoa trees was 972 trees per hectare and the average total yield was 897 kg/ha of dried cocoa beans. On site, cocoa pod husk management occurs, with all producers composting between 25% and 75% of total pod residues, whereas the remaining fraction is returned directly to the field, where they undergo natural decomposition.

The cocoa beans are then freighted by road to the chocolate manufacturing plant, located in the city of Pisco (13°42′36″S; 76°12′12″W), in coastal-central Peru, approximately 200 km south of Lima. Chocolate manufacturing consists of two main stages. Firstly, beans are processed and converted into four cocoa intermediate products (i.e., cocoa liquor, cocoa butter, cocoa powder, and cocoa cake). In the second stage these intermediate products are mixed with sugar and other ingredients to obtain the final chocolate products. In this study, three products are analyzed: i) white organic chocolate drops (45%); ii) organic chocolate drops (55%); and iii) organic chocolate kibbles (55%). The main ingredient characteristics of the 3 products can be seen in Table 1.

**Table 1.** Main ingredients used in the formulation of the organic chocolate products analyzed. Data reported in grams per functional unit (FU): 1 kg of final chocolate product placed at the port ready for export in year 2022

| **Ingredients** | **White chocolate drops (45%)** | **Chocolate drops (55%)** | **Chocolate kibbles (55%)** |
|---|---|---|---|
| Cocoa liquor | -- | 370 | 310 |
| Cocoa butter | 450 | 180 | 240 |
| Organic sugar | 299 | 450 | 450 |
| Tapioca starch | 190 | -- | -- |
| Rice syrup | 40 | -- | -- |
| Organic rice maltodextrin | 20 | -- | -- |
| Vanilla powder | 1 | -- | -- |

A steady-state retrospective attributional LCA model was established using data primarily from the year 2022. The system boundaries were divided into two main blocks, as illustrated in Figure 1. The first stage is comprised of the cultivation sites in Satipo, including the nursery stage, up to the delivery of the cocoa beans at the gate of the chocolate manufacturing plant. The second stage represents chocolate manufacturing system, which includes all the processes to transform cocoa beans into the three final chocolate products, including storage and transportation from the plant to the export port.

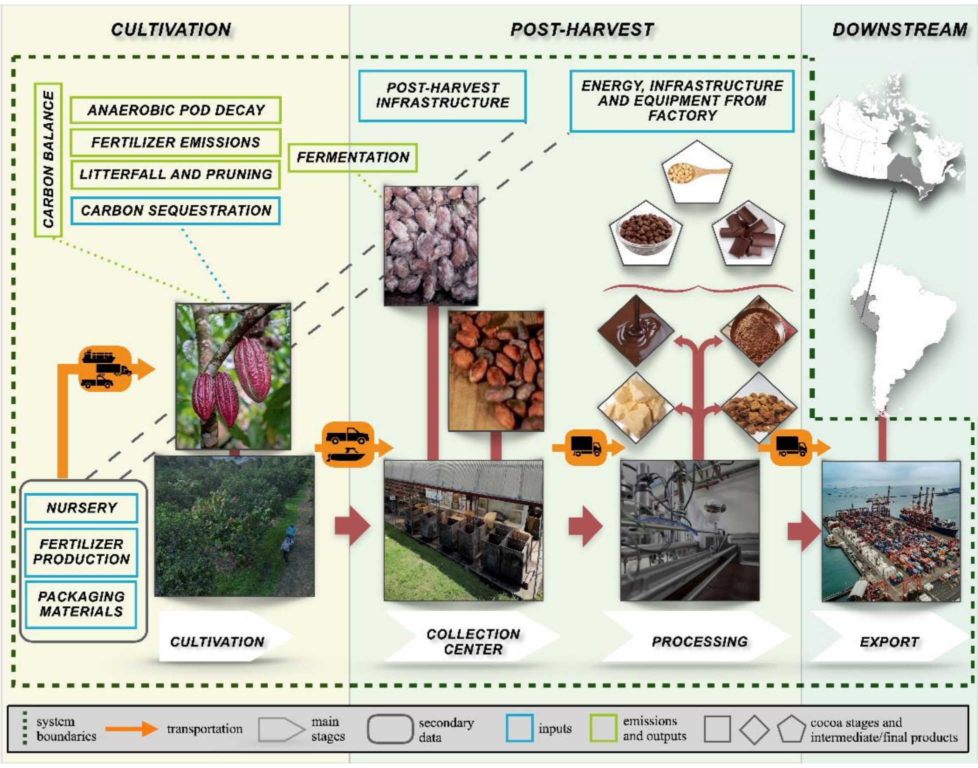


**Figure 1.** Cradle-to-gate system boundary to produce organic chocolate products in Peru.

### *3.2 Function of the production system*

The function of the system was fixed as the delivery of a finalized organic chocolate product ready for export at the port of Pisco in Peru. Hence, the FU selected was 1 kg of each chocolate product placed at the port ready for export in year 2022. However, results from the cultivation stage are also presented for organic cocoa beans ready for chocolate production as an intermediate product. For this, an intermediate FU was selected and fixed as 1 kg of dried cocoa beans ready to unload from a delivery truck at the plant in Pisco.

### *3.3 Data acquisition*

Data collection with farmers and technical personnel at the chocolate plant commenced with a workshop in May 2023 to deliver basic knowledge on life cycle methodologies, so they could familiarize themselves with the data needs of the study and understand the type of results it would deliver. Thereafter, a set of technical visits were planned to visit the cultivation sites in Satipo and the chocolate plant in Pisco. The next step consisted of the production of a full questionnaire by LCA practitioners, which was iterated with the technical team at MPF prior to its use. The questionnaire, which can be seen in Section SM1 of the Supplementary Material (SM), covers all the critical data points of the production system. Most data in both stages were collected by means of the questionnaire, and, in a second step, the data were confirmed and validated by the plant technicians via emails or Zoom meetings when necessary.

Primary data obtained from producers were then integrated with a set of secondary data that were used to complete the foreground system under study. Hence, emissions linked to the use of organic fertilizers, combustion in transport vehicles, stationary structures for fermenting and drying cocoa and other emissions such as those from tire abrasion, were modeled using updated emission factors based on the available scientific literature.

### *3.3.1 Secondary data sources*

In the cultivation stage, on-field fertilizer emissions were modeled considering the emission factors suggested by different environmental agencies (i.e., EEA and IPCC). Fertilizer emissions to air, including ammonia ($NH_3$), nitrous oxide ($N_2O$) and nitrogen oxide ($NO_x$), were accounted for as outlined in Table 2. $NH_3$ emissions were modeled as described by Nemecek and Kägi (2007). $N_2O$ and $NO_x$ emissions were modeled based on various bibliographical sources, with $N_2O$ method scenarios detailed in the subsequent sensitivity analysis section. Emissions to water bodies of nitrates ($NO_3^-$), phosphates ($PO_4^{3-}$) and phosphorus (P) were considered. For $NO_3^-$ water emissions, the emission factor from IPCC 2006 was applied to quantify the N input influence (IPCC, 2006). $PO_4^{3-}$ leaching and phosphorus emissions through erosion, derived from organic P content, were calculated using the emission factor from Nemecek and Kägi (2007).

**Table 2.** Description of emission factor calculations for substances emitted on-field to the air and water compartments related to fertilizer application. Although emission factors are also shown for inorganic (i.e., mineral) fertilizers, it should be noted that most inorganic fertilizers cannot be applied in organic cultivation sites. In contrast, certain mineral fertilizers, such as dolomite or rock phosphate are allowed in organic practices.

| Substance | Type of fertilizer | Action taken |
|---|---|---|
| **Emissions to air** | | |
| Ammonia ($NH_3$) | Organic | Emission factors were calculated based on the model provided by Nemecek and Kägi (2007) for solid poultry manure to compute ammonia emissions from '*guano de isla*'. Emission factor of 106 mg $NH_3$ per kg dried poultry manure. |

| | | |
|---|---|---|
| | Inorganic | These emissions are dependent on the type of mineral fertilizer, according to the recommendations provided by the IPCC (IPCC, 2006). The emission factor (% of total N) was as follows:<br>-8 for ammonium sulphate (AS).<br>-2 for ammonium nitrate (AN).<br>-2 for calcium ammonium nitrate (CAN).<br>-15 for urea.<br>-8 for urea ammonium nitrate (UAN).<br>-5 for di-ammonium phosphate (DAP).<br>-2 for mono-ammonium phosphate (MAP).<br>-2 for NPK fertilizers. |
| Nitrous oxide<br>($N_2O$) | Organic | For the modeling of these emissions, four different methods were considered. First, the IPCC standards from 1996 (IPCC, 1996). A second approach used the IPCC, Tier 1, standards from 2006 (IPCC, 2006). Furthermore, the emission factors reported for tropical environments, in loamy soils, by Marquina et al. (2013) were also used to compute these emissions. Finally, the default emission factors to estimate direct $N_2O$ emissions from managed soils were obtained from Chapter 11 of the updated IPCC 2019 standards (IPCC, 2019), this method was used to report the main results, whereas the remaining three methods were used as part of the sensitivity analysis. |
| | Inorganic | |
| Nitrogen oxides<br>($NO_x$) | Organic | An emission factor of 2.6% kg $NO_x$ - N/kg N applied was used (EEA, 2013). |
| | Inorganic | |
| **Emissions to water** | | |
| Nitrate<br>($NO_3^-$) | Organic | The emissions were calculated as follows:<br>$NO_3^-$ - N (kg/ha) = N input (kg/ha) * emission factor.<br>The EF for mineral fertilizer and livestock manure was assumed to be 0.3, according to IPCC (2006). |
| | Inorganic | |
| Phosphate leaching to ground water and run-off to surface water ($PO_4^{3-}$)<br>& Phosphorus to surface water (P) | Organic | Emission factors were calculated based on the model provided by Nemecek and Kägi (2007). |
| | Inorganic | |

For the manufacturing stage, emissions quantification from fuel combustion were based on national reports (Osinergmin, 2021, Infocarbono Peru, 2023). However, for emissions from heavy metals, the European EMEP/EEA air pollutant emission inventory guidebook 2023 was used (EEA, 2023). Two types of fuel were utilized: natural gas and liquefied petroleum gas (LPG). Natural gas was employed in the boilers to heat water and melt the chocolate. LPG was used for lift trucks responsible for organizing and distributing products within the warehouse.

In terms of fugitive emissions from the use of refrigerants (i.e., cooling agents), R-140-A was the main refrigerant used for air conditioning and heat pump equipment. Its production modeling was included considering that it is a zeotropic mixture of R-32 and R-125 (Heredia-Aricapa et al., 2020). Regarding emissions, the characterization factors (CFs) used were 771 kg $CO_2$eq/kg for R-32 and 3740 kg $CO_2$eq/kg for R-125 (IPCC, 2021). The emission factor considered was 8% of the annual use of the refrigerant. However, in terms of production, the ecoinvent® v3.7.1 dataset for R-134a production was used as an approximation due to lack of data for these specific refrigerants.

### *3.4 Methodological choices and limitations*

A series of methodological choices were considered in the construction of life cycle modelling. First, no allocation between co-products was necessary in the cultivation stage, as it was considered that cocoa beans were the only marketable product exiting the agricultural system. For the manufacturing stage, economic allocation was chosen in derivative production processes, due to substantial disparities in the pricing of primary products (nibs) and by-products (cocoa hulls). The choice of economic allocation aims to prevent overestimation of low-value by-products, such as cocoa hulls, which despite being produced in significant quantities, provide minimal economic revenue compared to the nibs.

At the cocoa producing sites, the nursery stage was included in the life cycle modelling (see Figure 1), based on bibliographical data exclusively, as we were unable to retrieve primary data. Furthermore, a limitation in the modelling of freight-derived emissions is linked to the fact that dust and sand particles, which drift in roads in many areas of the Peruvian road system, especially along the hyper-arid coast (e.g., the 220 km along the Panamerican Highway between Lima and Pisco), are not included in the system boundaries of the study, although they could increase the particle emissions considerably (Verán-Leigh et al., 2019).

In the manufacturing stage, primary data for certain energy and material flows (e.g., electricity consumption and use of cooling agents) were obtained at a plant level. In this case, mass allocation was established to partition these flows between the three products selected for the assessment and other products that are produced at the plant. While this is a potential source of uncertainty, plant technicians did not expect significant distortions through this methodological choice, as all production lines have similar processes and energy requirements. Finally, regarding sugar provision, while secondary data from the ecoinvent® v3.7.1 database was used to model average Brazilian production conditions, it is expected that these values could be a source of uncertainty due to the relative importance of sugar in terms of total mass content. As stated below in section 3.7, sugar was modelled with and without considering LUCs.

### *3.5 Life Cycle Inventory*

The Life Cycle Inventory (LCI) is presented in Tables 3 and 4 for the two separate stages of the study. Table 3 details the inventory per FU considering the final organic chocolate products. Data per kilogram of dry cocoa beans delivered to the chocolate manufacturing plant can be seen in Table SM3 in the SM, and data per hectare of cocoa production are shown in Table SM4.

**Table 3.** Summarized Life Cycle Inventory (LCI) data of subsystem I – Organic cocoa bean production and delivery. Data reported per FU: 1 kg of packaged organic chocolate product ready for export at port.

| Inputs | Unit | White chocolate drops (45%) | Chocolate drops (55%) | Chocolate kibbles (55%) |
|---|---|---|---|---|
| Water | g | 4.05 | 4.62 | 4.62 |
| Poultry manure | g | 315.7 | 368.4 | 368.4 |
| Organic nitrogen fertilizer, as N | g | 59.00 | 68.85 | 68.85 |
| Silica sand | g | 71.26 | 83.15 | 83.15 |
| Phosphoric rock | g | 139.0 | 162.2 | 162.2 |
| Dolomite | g | 170.0 | 198.4 | 198.4 |
| Packaging for fertilizers | g | 0.35 | 0.41 | 0.41 |
| Jute fiber | g | 3.18 | 3.71 | 3.71 |

| Outputs | Unit | | | |
|---|---|---|---|---|
| **Dry organic cocoa beans** | **g** | **585.25** | **682.89** | **682.88** |
| ***Waste*** | | | | |
| Plastic waste | g | 0.21 | 0.24 | 0.24 |
| ***Emissions to air*** | | | | |
| Ammonia ($NH_3$) | g | 1.40 | 1.64 | 1.64 |
| Dinitrogen monoxide ($N_2O$) | g | 0.89 | 1.03 | 1.03 |
| Nitrogen oxides ($NO_x$) | g | 2.45 | 2.86 | 2.86 |
| PM2.5 | g | 4.14 | 4.83 | 4.83 |
| Carbon dioxide ($CO_2$) – cocoa pod husk management | kg | 4.57 | 5.33 | 5.33 |
| Carbon dioxide ($CO_2$) – litterfall | kg | 3.56 | 4.16 | 4.16 |
| Carbon dioxide ($CO_2$) – prunning | kg | 4.40 | 5.13 | 5.13 |
| ***Emissions to water*** | | | | |
| Nitrate | g | 124.9 | 145.7 | 145.7 |
| Phosphate | g | 0.48 | 0.56 | 0.56 |
| Phosphorus | g | 2.07 | 2.41 | 2.41 |
| ***Carbon capture*** | | | | |
| Carbon dioxide ($CO_2$) – total capture | g | 10.49 | 12.24 | 12.24 |

Table 4 shows the main data related to the main activities and emissions occurring at the chocolate processing plant to produce the three chocolate products under assessment.

**Table 4.** Summarized Life Cycle Inventory (LCI) data of subsystem II – Chocolate manufacturing. Data reported per FU: 1 kg of packaged organic chocolate product ready for export at port.

| Inputs | Unit | White chocolate drops (45%) | Chocolate drops (55%) | Chocolate kibbles (55%) |
|---|---|---|---|---|
| Organic cocoa butter | g | 450.0 | 180.0 | 240.0 |
| Organic sugar | g | 299.0 | 450.0 | 450.0 |
| Organic cocoa liquor | g | -- | 370.0 | 310.0 |
| Tapioca starch | g | 190.0 | -- | -- |
| Rice syrup | g | 40.00 | -- | -- |
| Organic rice maltodextrin | g | 20.00 | -- | -- |
| Electricity | kWh | 1080 | 1223 | 1244 |

| | | | | |
|---|---|---|---|---|
| Polyethylene bags | g | 0.41 | 0.41 | 0.41 |
| Cardboard | g | 32.67 | 32.67 | 32.67 |
| Transport by sea of sugar from Brazil to Peru | kgkm | 2614 | 3935 | 3935 |
| Transport by road of sugar to the plant in Pisco | kgkm | 70.86 | 106.7 | 106.7 |
| Transport by sea of tapioca starch from Thailand to Peru | kgkm | 3919 | -- | -- |
| Transport by road of tapioca starch to the plant in Pisco | kgkm | 45.03 | -- | -- |
| **Outputs** | **Unit** | **Amount** | | |
| **White organic chocolate drop (45%)** | **kg** | **1** | **--** | **--** |
| **Organic chocolate drops (55%)** | **kg** | **--** | **1** | **--** |
| **Organic chocolate kibbles (55%)** | **kg** | **--** | **--** | **1** |
| Cocoa butter carboard - waste | g | 8.82 | 3.53 | 4.70 |
| Cocoa liquor cardboard - waste | g | -- | 6.04 | 5.06 |
| Emission of R-32 (cooling agent) | mg | 5.18 | 5.18 | 5.18 |
| Emission of R-125 (cooling agent) | mg | 5.18 | 5.18 | 5.18 |
| Waste Sugar Kraft Paper Sacks | g | 1.22 | 1.84 | 1.84 |
| Waste Starch Kraft Paper Sacks | g | 0.78 | -- | -- |
| Waste polyethylene bags | g | 0.01 | 0.01 | 0.01 |

### *3.6 Modelling the carbon cycle*

A full carbon cycle at the cultivation sites was modelled to account for the carbon storage and biogenic carbon emissions that occur and have shown to be relevant in prior scientific literature, following a methodology proposed in an article in progress by González-Socorro et al. (in preparation). In terms of carbon emissions, fermentation of cocoa beans during the post-harvest stage were accounted for utilizing an emission factor of 56.22 kg $CO_2$/t of dry cocoa beans produced (Hernandes et al., 2022). The decomposition of cocoa pod husks on fields, which tend to be methane-intensive, was modelled according to IPCC guidelines for solid waste disposal (Eggleston et al., 2006), as shown in Equation 1, assuming that all pods stay on the ground at each site under semi-aerobic conditions (i.e., 50% emitted as methane and 50% emitted as $CO_2$):

$$CH4\ emissions = W * DOC * DOCf * MCF * F * \left(\frac{16}{12}\right) \qquad \text{[Eq. 1]}$$

where W represented the mass of cocoa pod waste deposited on each field, DOC represents the degradable organic carbon in percentage of wet waste (a value of 0.2 was assumed), $DOC_f$ is the fraction of DOC that can decompose (a 0.5 default value was selected as recommended by IPCC), MCF is the methane correction factor for aerobic decomposition, which in the current study depended on the rate of composting per producer; F represents the fraction of methane (a 0.5 default value was selected as recommended by IPCC), and 16/12 the molecular weight ratio methane/carbon.

Regarding litterfall decomposition, the IPCC model was followed, considering a logistic variation over time and 80% aerobic decomposition (Ewel, 1976). Moreover, the carbon filtration rate of 13% was modelled to account for carbon that is captured in the soil (Rubino et al., 2007). Finally, concerning the decomposition of pruning residues, litterfall derived from pruning was modelled in the same way as the natural litterfall process described above. In contrast, woody pruning residues were modelled following the IPCC models but at a slower rate and assuming 90% aerobic decomposition (Ledo et al., 2018). All pruning residues were assumed to remain on the ground at each site.

It should be noted that for all carbon dioxide (i.e., $CO_2$) emissions described, it was assumed, following the recommendation by Jeong et al. (2015), that 10% of the $CO_2$ generated is dissolved in water. While this recommendation is based on the canalization of water in landfills, it was considered a good proxy considering the humid conditions in cocoa cultivation sites.

In terms of carbon capture, above-ground biomass (AGB) of cocoa and shade trees was estimated based on allometric equations as modelled by Andrade et al. (2012), whereas other trees were modelled using a general equation for tropical trees (Pearson et al., 2005), as shown in Section SM3 of the SM. Root biomass was obtained by assuming that aboveground biomass represents ca. 87% of plant biomass for cocoa trees (Norgrove and Hauser, 2012), whereas for shading trees the estimation was performed based on the equation provided by Cairns et al. (1997). In the case of soil carbon sequestration, it should be noted that primary data were obtained from an experimental cocoa cultivation plot in Boliva with similar edaphic and climatic conditions to those in the current study. The calculation was based on a land analysis performed in two different years (i.e., 2010 and 2020), and the balance between these two periods was then allocated, assuming constant carbon retention in soil (Krause et al., under review).

### *3.7 Life Cycle Impact Assessment*

The Life Cycle Impact Assessment (LCIA) stage was conducted considering a set of 8 impact categories, listed in Table 5. The choice of impact categories was based on the inclusion of carbon and water footprint-related categories, such as global warming (GW), water scarcity (WS) and freshwater eutrophication (FEu), as well as additional impact categories linked to toxicity (i.e., freshwater eco-toxicity – FET, and human toxicity) and air pollution (i.e., fine particulate matter formation – FPMF).

**Table 5.** List of impact categories with their assessment methods and reference unit included in the calculation of cocoa-based products manufactured in Peru.

| **Impact category** | **Acronym** | **Unit** | **Original assessment method** | **Reference** |
|---|---|---|---|---|
| Water scarcity | WS | $m^3$eq | AWARE v1.01 | Boulay et al. (2018) |
| Terrestrial acidification | TA | g $SO_2$eq | ReCiPe 2016 | Huijbregts et al. (2016) |
| Freshwater eco-toxicity | FET | PAF * $m^3$ * day | USEtox 2.0 | Rosenbaum et al. (2011) |
| Freshwater eutrophication | FEu | g Peq | ReCiPe 2016 | Huijbregts et al. (2016) |
| Global warming | GW | kg $CO_2$eq | IPCC 2013 | IPCC (2013) |
| Human toxicity – cancer | HT-C | CTUh | USEtox 2.0 | Rosenbaum et al. (2011) |
| Human toxicity - non-cancer | HT-NC | CTUh | USEtox 2.0 | Rosenbaum et al. (2011) |
| Fine particulate matter formation | FPMF | g PM2.5 eq | ReCiPe 2016 | Huijbregts et al. (2016) |

All impact categories were modelled in the SimaPro v9.6.0.1 software (PRè Sustainability, 2024), except for the AWARE impact category for WS. For the latter, a hybrid computation was considered using SimaPro and Excel spreadsheets, in which foreground system water flows occurring within Peru were modelled with the CFs reported by Sánchez-Matos et al. (2024), which update those reported in the original AWARE model. Similarly, for the case of direct water use in the cultivation of sugarcane in Brazil, CFs from Costa et al. (2022) were used. For all other water flows within the

LCI, the default values from the ecoinvent v3.7.1 database were used, as well as the national average CFs. Regionalized CFs used in the current study are shown in Table SM5 of the SM.

### *3.8 Scenario and sensitivity analyses*

Scenario and sensitivity analyses were carried out to understand how the results vary depending on changing assumptions. For cocoa beans delivered to the manufacturing plant, three parameters were considered critical to understand the sensitivity of the results: i) the modeling of $N_2O$ emissions; ii) the modeling of the road freight emissions of the dried cocoa beans from Satipo to Pisco; and, iii) the management at the cultivation site of the cocoa pod residues. The first two are linked to data quality, whereas the latter modeling is related to scenario analysis. A "baseline scenario" was modeled using a full accountability of the primary data obtained at the farms, based on IPCC 2019 guidelines for $N_2O$ emissions from fertilizers use in the field, considering diesel consumption reported by the trucks transporting cargo from Satipo to Pisco, as well as composting rates (%) reported by individual cultivation sites. A second scenario, as shown in Table 6, referred to as the "low-carbon scenario", also utilized IPCC 2019 for $N_2O$ emission, but it employs an ecoinvent process to model road freight transport and includes full composting of cocoa pods under ideal conditions. In other words, the latter scenario models environmental impacts, namely GHG emissions, assuming that certain climate actions are already enforced at the farms.

**Table 6.** List of scenarios modeled for the cultivation stage of dry cocoa bean production in Satipo.

| Scenario | $N_2O$ emissions | Cocoa pod management | Road freight emissions to chocolate processing plant |
|---|---|---|---|
| Baseline Scenario | IPCC 2019 | Composting rate reported by farmers. The composted amount assumes ideal conditions | Modeled according to diesel consumption reported by MPF |
| Low-carbon scenario | IPCC 2019 | Full composting under ideal conditions | ecoinvent process |
| F1 | IPCC 1996 | Full composting under ideal conditions | ecoinvent process |

| | | | |
|---|---|---|---|
| F2 | IPCC 2006 | Full composting under ideal conditions | ecoinvent process |
| F3 | Marquina et al. (2013) | Full composting under ideal conditions | ecoinvent process |
| H1 | IPCC 2019 | Natural decomposition of cocoa pod on field | ecoinvent process |
| H2 | IPCC 2019 | Composting rate reported by farmers. Composted amount assumes ideal conditions | ecoinvent process |
| H3 | IPCC 2019 | Full composting under ideal conditions | Modeled according to diesel consumption reported by MPF |

The sensitivity analysis took into consideration two critical variables: the emission factor used for $N_2O$ emissions (i.e., scenarios F1-F3), and transportation modelling (i.e., scenario H3). The scenario analysis considered distinctive farm-focused variabilities, each adopting varying treatment approaches for the anaerobic emission of cocoa pods. The first scenario is the natural decomposition of cocoa pods on field (H1), the second scenario (H2) assumes a business-as-usual approach, accounting for the declared composting practices by farmers in the inventory, resulting in a reduced percentage of $CH_4$ emissions as compared to natural decomposition, and the third scenario (H3) considers an ideal scenario in which all residues from cocoa pods are composted. For the manufacturing stage, two alternative scenarios were considered. Scenario S1 accounts for secondary data on sugar production in Brazil including land use changes (LUCs), whereas scenario S2 models the same system without the consideration of LUCs. The inclusion of the latter allows to establish whether average LUCs rates from sugar production have a relevant contribution to GHG emissions in the system under analysis.

## 4. Results and discussion

### *4.1 Environmental assessment results of cocoa beans production and delivery to the manufacturing plant*

WS results ranged from 0.50 $m^3$/kg of dried cocoa beans to 4.12 $m^3$/kg, with a weighted mean value of 1.27 $m^3$/FU (see Table 7). Given that there is no irrigation in the cultivation sites assessed thanks to recurrent rainfall through the year, the main driver of WS results was found to be the upstream production of organic N-fertilizer, followed by other fertilizers, such as potassium sulfate or phosphoric rock. In this respect, farmers reported annual *guano de isla* fertilization use ranging from 567 kg/ha to 1391 kg/ha. In fact, the farmer with the highest WS result used 1354 kg/ha of *guano de isla*. Sites with the lowest harvest yields (i.e., 311 kg/ha and 280 kg/ha) were found to be those with the highest WS results, and the field with the highest intensity use of *guano de isla* presented the third-highest result.

**Table 7.** Environmental impact results per 1 kg of dry cocoa beans ready to be delivered at the chocolate processing plant. Results presented per weighted mean values and include weighted standard deviation.

| Impact category | Unit | FU of dry cocoa bean per field | | |
|---|---|---|---|---|
| | | **Weighted mean and SD** | **Minimum value** | **Maximum value** |
| WS | $m^3eq$ | 1.27±0.60 | 0.50 | 4.12 |
| TA | g $SO_2eq$ | 13.45±6.30 | 5.53 | 43.16 |
| FET | PAF $m^3eq$ | 0.18±0.09 | 0.07 | 0.61 |
| FEu | g P eq | 0.56±0.22 | 0.32 | 1.44 |
| GW (fossil emissions only) | kg $CO_2eq$ | 1.62±0.62 | 0.86 | 4.54 |
| GW (full carbon balance) | kg $CO_2eq$ | 5.18±5.17 | -5.37* | 22.98 |
| HT-C | CTU h | 8.71E-10±7.75E-11 | 7.76E-10 | 1.14E-09 |
| HT-NC | CTU h | 8.92E-09±5.13E-10 | 9.32E-09 | 1.07E-08 |
| FPMF | g PM2.5 eq | 3.96±1.41 | 2.56 | 10.54 |

*The negative value for GW accounting for full carbon balance is explained by higher capture processes from different carbon sinks on field than the sum of fossil and biogenic carbon emissions.
Results per producer can be found in Tables SM7-SM9 of the Supplementary Material (SM).

In terms of terrestrial acidification (TA), results ranged from 5.53 g $SO_2eq$/kg to 43.16 g $SO_2eq$/kg. The weighted mean TA result was 13.46±6.30 g $SO_2eq$. The cultivation stage was the main contributor to higher TA results, although higher yields were associated with lower TA results. More specifically, field-related activities represented 70%-80% contribution for all producers, while transportation ranged from 19% to 25%. Within the cultivation stage, emissions from N-fertilizers were the main contributing activity representing ca. 65% of total impacts.

FEu results ranged from 0.33 g Peq/kg to 1.44 g Peq/kg. Phosphate and phosphorus run-off from the application of phosphoric rock in the cultivation site represented the main source of environmental impact (>50%), followed by the upstream production of fertilizers, such as *guano de isla* (ca. 18%) or dolomite (ca. 5%). In addition, other post-harvest activities throughout the supply chain (i.e., transportation and material for packaging) contributed less than 7% of the total impact.

The final water-related impact category assessed, i.e., FET, showed results that ranged from 0.07 PAF*$m^3$*day/kg to 0.61 PAF*$m^3$*day/kg, with a similar distribution as the TA results through the different producers and a weighted overall mean of 0.16 PAF*$m^3$*day/kg. Higher application rates of *guano de isla* per hectare were related to higher FET values, being the main hotspot for this category. The secondary driver of FET impacts is the transportation linked to cocoa bean production, contributing ca. 1% of total impacts. Additionally, jute weaving production for packaging represented ca. 2% of the FET result, followed by minor contributions of dolomite, potassium sulfate and phosphoric rock productions.

Regarding the impact categories that are non-water related, specifically GW impacts, which are shown in Table 7 with and without consideration of the biogenic carbon balance, show important differences in GHG emissions that can be identified between producers. If fossil GHG emissions are considered alone, the weighted mean emissions per kg of dry cocoa beans were 1.62 kg $CO_2$eq, ranging from 0.86 kg to 4.54 kg $CO_2$eq. Emissions from fertilizers, both due to manufacturing and direct on-field emissions were the main drivers of these fossil emissions. However, when biogenic emissions are considered that include the full carbon cycle of cocoa production, the weighted mean value of 5.18 kg $CO_2$eq per kg is attained, with a range from -5.37 kg $CO_2$eq to 22.98 kg $CO_2$eq.

The biogenic carbon balance implies a net emission of 3.56 kg $CO_2$eq/kg when a weighted average is considered for the full sample of cultivation sites. Anaerobic decomposition of the cocoa pods (7.81 kg $CO_2$eq/kg), followed by pruning (7.51 kg $CO_2$eq/kg) and litterfall (6.09 kg $CO_2$eq/kg) are the main sources of carbon emissions, adding up to a total of 21.47 kg $CO_2$eq/kg, whereas carbon capture, which adds up to 17.92 kg $CO_2$eq/kg, is dominated by aboveground biomass followed by SOC sequestration. When divided by cocoa production system, as shown in Figure 2, producers with agroforestry systems showed the lowest GHG emissions per unit of dried cocoa beans produced (i.e., 0.38 kg $CO_2$eq/kg), thanks mainly to a higher level of aboveground biomass capture (24.4 kg $CO_2$eq/kg) as compared to the two other production systems and, to a lesser extent, to a limited amount of fertilizer application. The monocrop system was the second with the highest carbon capture potential per kilogram of produced cocoa beans (i.e., 17.84 kg $CO_2$eq/kg); however, the higher emissions from pod decomposition, litterfall, pruning and fertilizer application, raise the total GHG emissions to 11.16 kg $CO_2$eq/kg. Finally, intercrop cocoa-fruit systems show lower average GHG emissions than monocrops (i.e., 5.41 kg $CO_2$eq/kg) thanks to a higher composting rate of the pod residues, whereas the carbon capture is the lowest of the three systems (i.e., 15.55 kg $CO_2$eq/kg).

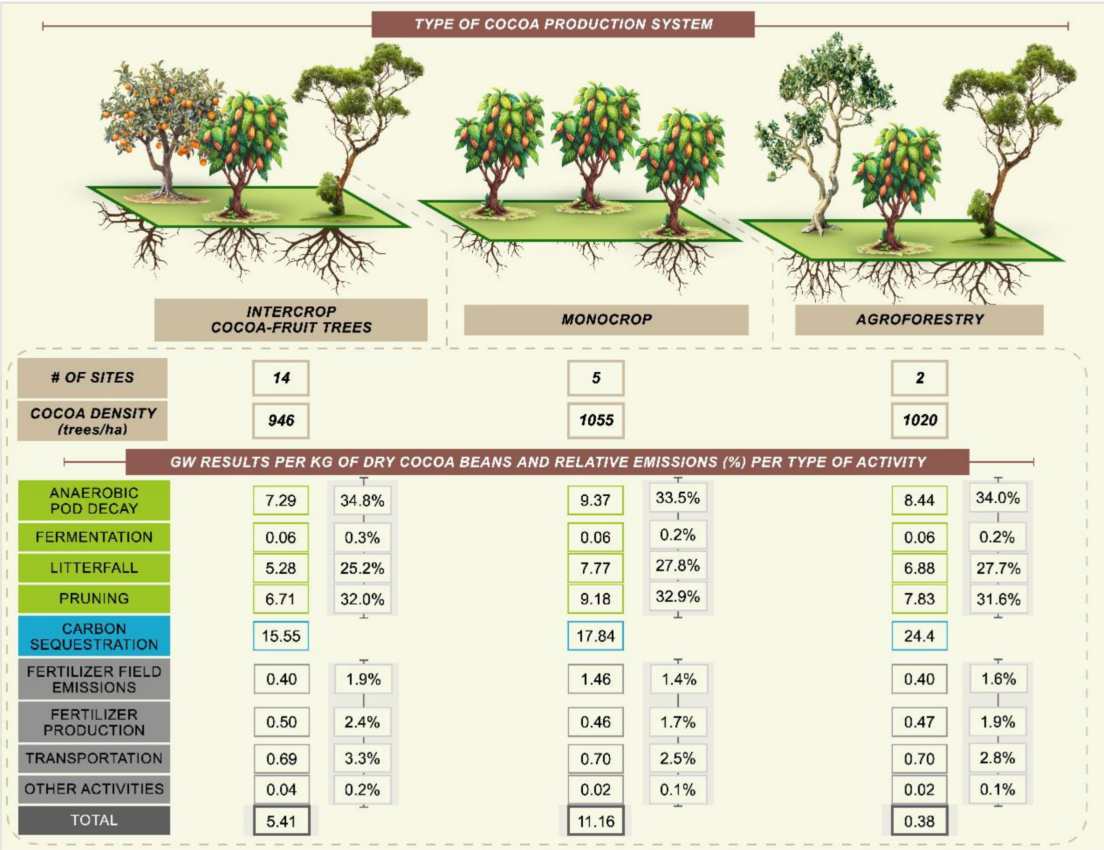


**Figure 2.** Global warming (GW) impact results per kilogram of dry organic cocoa beans delivered to the manufacturing plant. Results are expressed in kg $CO_2$eq and constitute a weighted average of the 21 producers inventoried. Activities highlighted in green represent biogenic carbon emissions at the cultivation sites, whereas the activity in blue represents the carbon capture at the sites. Activities in light grey show fossil carbon emissions.

The results comparing production systems, while in similar ranges with the revised scientific literature (e.g., Avadí, 2023), must be interpreted with care, as the sample size for agroforestry (2 producers) and monocrops (5 producers) is low. Further research with additional sites would be useful to determine whether these tendencies are maintained with a statistically significant sample size.

Regarding FPMF formation, results demonstrate that the main contributors are direct emissions from the production system: i) PM2.5 emissions from TRWP; ii) emissions from the volatilization and run-off of fertilizers on field; and iii) emissions from the fermentation process and the decomposition of cocoa pod residues. FPMF results ranged from 2.24 to 10.54 g PM2.5/kg across the 21 production units. When analyzing the results for the worst-performing site, the main emissions were linked to emissions from the spreading of fertilizers on fields, mainly ammonia, which represented 36% of total particulate emissions. Transport emissions from fossil fuel combustion represent 25% of total emissions, followed by the production of *guano de isla* (21%). TRWP emissions accounted for 3% of total emissions. Considering that synthetic pesticides are not used at the cultivation sites, which are the agents that tend to increase the human toxicity impacts in these agri-food systems (Vázquez-Rowe et al., 2012), it is reasonable to assume that the values reported for the present production system are low as compared to conventional cocoa systems.

### *4.2 Environmental assessment results of the chocolate manufacturing stage*

Activities related to the chocolate manufacturing plant show in most cases lower impact per kilogram of final product, than the cultivation stage. However, when focusing on water-related impacts, WS shows a higher intensity in the manufacturing stage as compared to cocoa production. While these results may seem counterintuitive, as agricultural products tends to show higher water scarcity potential in the cultivation stage (García-Herrero et al., 2023), the results for chocolate production in Peru must be understood in context of extreme regional difference in WS potential and, therefore, in the derived environmental impacts when analyzing water scarcity impacts in the Amazon rainforest (cocoa cultivation), where CFs are > 2 $m^3$eq/$m^3$ and the Peruvian coast (chocolate factory), where the watershed under evaluation (i.e., the Pisco watershed) shows an annual CF of 32 $m^3$eq/$m^3$ (Sanchez-Matos et al., 2024). In this sense, the WS impacts per FU ranged between 3.84 and 4.95 $m^3$eq/FU (see Table 8), with a major role of electricity production and especially direct consumption of water at the plant.

**Table 8.** Environmental impact results of the impact categories selected related to the production of 1 kg of each final organic chocolate product (results are reported per functional unit – FU, i.e., 1 kilogram of final organic chocolate product ready for marine freight to port of destination). Results represent the manufacturing stage at the chocolate-producing factory, as well as the upstream production of sugar.

| Impact category | Unit | White chocolate drops (45%) | | Chocolate drops (55%) | | Chocolate kibbles (55%) | |
|---|---|---|---|---|---|---|---|
| | | **S1** | **S2** | **S1** | **S2** | **S1** | **S2** |
| WS | $m^3$eq | 3.86 | 3.84 | 3.89 | 3.87 | 3.95 | 3.93 |
| TA | g $SO_2$eq | 4.74 | 3.51 | 3.36 | 1.51 | 3.36 | 1.50 |
| FET | PAF $m^3$eq | 3241 | 3217 | 2043 | 2018 | 1920 | 1912 |
| FEu | g Peq | 0.12 | 0.09 | 0.08 | 0.03 | 0.08 | 0.03 |
| GW | kg $CO_2$eq | 1.30 | 0.92 | 1.33 | 0.77 | 1.34 | 0.77 |
| HT-C | CTU h | 3.02E-08 | 3.01E-08 | 2.23E-08 | 2.11E-08 | 2.14E-08 | 2.08E-08 |
| HT-NC | CTU h | 1.22E-07 | 4.21E-08 | 1.49E-07 | 2.88E-08 | 1.48E-07 | 2.78E-08 |
| FPMF | g PM2.5eq | 1.28 | 1.03 | 0.90 | 0.52 | 0.90 | 0.52 |

S1= secondary data on sugar production in Brazil including land use changes (LUCs); S2= secondary data on sugar production in Brazil without the consideration of LUCs.

The GW category is of special interest, with results in this stage ranging from 1.30 kg to 1.34 kg $CO_2$eq/FU for S1 and 0.77 kg to 0.92 kg $CO_2$eq for S2, where LUCs are not considered. Hence, this indicates that LUCs related to the production of sugar have a significant impact on the overall carbon footprint of the chocolate product. When LUCs are excluded from the system, electricity consumption, the fuel-derived emissions from boilers and the fugitive emissions from cooling agents are the main sources of GHG emissions, as well as the production of tapioca starch in the case of the white chocolate drops product.

### *4.3 Aggregated results of chocolate production*

When the full production system is observed aggregating the results from both stages, white chocolate drops show slightly lower results for most impact categories when compared to the other final products, specifically when the S1 scenario is considered in the manufacturing stage, as shown in Table 9 (results for the S2 scenario can be seen in Table SM6 in the SM). This is due mainly to the use of a lower amount of cocoa per final product, as the alternative ingredients (e.g., tapioca) present a lower environmental impact per unit of mass throughout the environmental impacts assessed. In contrast, for FET (+58%) and HT-C (+34%) the impacts are considerably higher for white chocolate drops.

**Table 9.** Environmental impact results for final chocolate products for the 8 impact categories selected. Results are reported per functional unit (i.e., 1 kg of final organic chocolate product ready for export at port). Environmental impacts for the processing stage refer to Scenario S1.

| Impact category | Unit | Organic white chocolate drops (45%) | Organic chocolate drops (55%) | Organic chocolate kibbles (55%) |
|---|---|---|---|---|
| WS | $m^3$ | 4.60 | 4.75 | 4.81 |
| TA | g $SO_2$eq | 12.62 | 12.55 | 12.55 |
| FET | PAF * $m^3$ * day | 3241 | 2043 | 1920 |
| FEu | g Peq | 0.45 | 0.46 | 0.46 |
| GW (fossil emissions only) | kg $CO_2$eq | 2.34 | 2.54 | 2.55 |
| GW (full carbon balance) | kg $CO_2$eq | 4.33 | 4.87 | 4.88 |
| HT-C | CTUh | 3.05E-08 | 2.29E-08 | 2.20E-08 |
| HT-NC | CTUh | 1.25E-07 | 1.55E-07 | 1.54E-07 |
| FPMF | g PM2.5 eq | 3.60 | 3.60 | 3.60 |

When the full carbon balance is included regarding GHG emissions, it can be observed that organic white chocolate drops show the lowest emissions (i.e., 4.33 kg $CO_2$eq/FU), whereas the other two products are in a similar range close to 4.90 kg $CO_2$eq/FU. As seen in Figure 3, the cultivation of organic dried cocoa beans represents ca. 70% of these impacts, whereas the GHG emissions from the manufacturing plant are substantially lower on average.


**Figure 3.** Final Global Warming (GW) environmental impact results expressed in kilograms of $CO_2$eq per functional unit – FU (i.e., 1 kg of final organic chocolate product ready for export at port) for each final organic chocolate products and relative contributions per stage.

These GHG emissions values, however, are subject to changes when different assumptions in the production process are considered. In the first place, if agroforestry-sourced cocoa beans are modeled alone, organic chocolate drops GHG emissions would mount to 1.59 kg CO2eq/FU, 67% lower than the average value, whereas for cocoa beans sourced from intercrops the value would be 5.02 kg $CO_2$eq/FU, 3% higher than average. Finally, chocolate drops produced with cocoa beans from monocrops (8.95 kg $CO_2$eq/FU) would be 84% higher than the average value. It should be noted that the manufacturer does not separate cocoa beans based on the production system of origin, so these values do not respond to specific final products but do reflect the enormous potential of climate change mitigation of agroforestry systems when compared to other production systems. In fact, a previous study by Niether et al. (2020) found that agroforestry systems for cocoa can store up to 2.5 times more carbon than other production systems, in line with the results obtained in our study.

### *4.4 Scenario analysis and comparison with scientific literature*

For the sake of comparability with prior studies published in scientific literature, cocoa beans production results have been recalculated to a common reference value (i.e., 1 kg of dried cocoa beans). The mean GHG emissions results obtained in the baseline scenario including only fossil-related carbon emissions (i.e., 1.62 kg $CO_2$eq) are in the lower range of values identified in the literature (see Table 10), with values ranging from just under 1 kg $CO_2$eq/FU (Ivanova et al., 2020) to slightly over 4 kg $CO_2$eq/FU (Avadí, 2023). However, it should be noted that most of these computations do not include GHG emissions linked to fermentation and cocoa pod decomposition on field, excluding these carbon emissions from their system boundary, as well as carbon capture, and therefore underrepresenting the system under analysis. In fact, only the studies by Hernandes et al. (2022) and Ortiz-Rodriguez et al. (2016), as well as the current study, include these emissions with final values within the 1-4 kg $CO_2$eq range, regardless of the conventional or organic characteristics of the cultivation sites.

**Table 10.** Comparative greenhouse gas (GHG) emissions between the results computed in the current study and those available in the scientific literature. All the values have been recalculated to a common FU of 1 kg of dried cocoa beans. It should be noted that methodological differences between the studies exist that must be analyzed with further care.

| Study or scenario | Global warming (kg $CO_2$eq) (fossil emissions only) | Global warming (kg $CO_2$eq) (including biogenic carbon balance) | Organic or conventional production | Consider fermentation and pod decomposition emissions | Comments |
|---|---|---|---|---|---|
| Baseline scenario | 1.62 | 5.33 | OP | yes[3] | - |
| Low-carbon scenario | 1.20 | 0.10 | OP | yes[1] | - |
| F1 | 2.18 | 1.08 | OP | yes[1] | - |

| | | | | | |
|---|---|---|---|---|---|
| F2 | 1.48 | 0.37 | OP | yes[1] | - |
| F3 | 1.34 | 0.23 | OP | yes[1] | - |
| H1 | 1.20 | 8.83 | OP | yes[2] | - |
| H2 | 1.20 | 4.76 | OP | yes[1] | - |
| H3 | 1.62 | 0.52 | OP | yes[1] | - |
| Hernandes et al., 2022<br>Brazil | 2.01 | Not computed | OP | yes[1] | Production of organic farms with composting. |
| | 2.59 | Not computed | CP | yes[1] | Production of conventional farms with composting. |
| | 10.46 | Not computed | CP | no | No composting |
| Ortiz-Rodríguez et al., 2016<br>Colombia | 8.00 | Not computed | CP | yes[3] | Conventional monocrop. |
| | 8.89 | Not computed | CP | yes[3] | Agroforestry management. |
| Pérez-Neira et al. (2016)<br>Ecuador | 1.63 | Not computed | CP | no | -Average of 2 farms.<br>-Traditional management. |
| | 1.96 | Not computed | CP | no | -Average of 4 farms.<br>-Technified management. |
| Avadí (2023)<br>Ecuador | 4.04 | Range from<br>-14.89 to 3.22 | CP | no | -Average of 4255 farms.<br>-Commodity bean.<br>-Mean productivity of 0.24 t/ha of small producers. |
| | 2.65 | -7.30<br>(mean)<br>Range from<br>-9.96 to 2.79 | OP | no | -Average of 1042 farms.<br>-Organic beans (small producers).<br>-Mean productivity of 0.32 t/ha of small |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | producers. |
| | 1.84 | -4.30 | CP | no | -Average of 109 farms.<br>-Premium bean.<br>-Mean productivity of 0.35 t/ha of medium-size producer. |
| | 4.53 | -1.10 | CP | no | -Average of 87 farms.<br>-Regular bean.<br>-Mean productivity of 0.5 t/ha of big producer. |
| Ivanova et al., 2020<br>Ucayali-Peru | 0.17 | Not computed | CP | no | -Traditional management |
| | 0.93 | Not computed | OP | no | -Mean productivity of 0.8 t/ha of medium-technified management. |
| | 2.26 | Not computed | CP | no | -Mean productivity of 1.5 t/ha using semi-technified management. |
| | - | 24.69[a] | CP | no | -Traditional management |
| | - | 22.07[a] | OP | no | -Mean productivity of 0.8 t/ha using medium-technified management. |
| | - | 13.71[a] | CP | no | -Mean productivity of 1.5 t/ha using semi-technified management. |

OP: organic production; CP: conventional production.

yes[1]: full composting under ideal conditions; yes[2]: natural decomposition on field; yes[3]: composting rate reported by farmers; no[1]: the modelling includes GHG emissions related to deforestation from land use changes.

[a]Land use changes only.

In the current study, we find that our scenarios range, on average, between 1.20 kg $CO_2$eq/kg of dried cocoa beans and 2.18 kg $CO_2$eq/kg when fossil-related carbon emissions are modeled only. However, as discussed above, the variability between producers is high because of different management systems, yields, and organic fertilizer application rates.

When the full carbon balance is computed, the activity that influences a potential reduction of GHG emissions from 5.33 kg $CO_2$eq in the baseline scenario to ca. 1 kg $CO_2$eq is the management of the residual cocoa pods. Therefore, if the cocoa pods are fully managed through adequate composting, GHG emissions are reduced substantially, with agroforestry systems capturing further carbon and the other two production systems contributing relatively low carbon emissions. However, composting modeled in our study assumes optimal composting conditions, so it should be noted that GHG emission mitigations may be slightly overestimated. Moreover, not returning the cocoa pod husks to the fields would probably result in higher spreading rates of certain fertilizers, especially those rich in potassium (Kone et al., 2020), which would also reduce the mitigation potential of this action. In contrast, the natural decomposition of cocoa pods on-site (i.e., scenario H1), with high methane emissions, would generate a full carbon balance of 8.83 kg $CO_2$eq/kg, closer to the values that have been previously reported for Ortiz-Rodriguez et al. (2016) in Colombia.

Currently, research is being conducted to valorize cocoa pod husks towards alternative uses, through physico-chemical, thermochemical or biochemical pathways (Ouattara et al., 2021), thanks to their high content in lignocellulose, pectin, potassium or phenols (de Souza Vandenberghe et al., 2022). Hence, pod husks are starting to be employed for an array of different final products, that include their use for energy (Dahunsi et al., 2019), for extracting certain antioxidants (Lu et al., 2018), as animal feed (Campos-Vega et al., 2018), or paper production (Hatta, 2013), among others. In this sense, future research in cocoa/chocolate LCA should delve into the environmental impacts of these valorization pathways, to establish their effect on the full system, in which multifunctionality would emerge as a new methodological challenge in the life cycle modelling. However, it should be noted that cocoa bean and cocoa husk removal from soils contributes to nutrient deficit (Fidelis and, Rajashekhar Rao, 2017); hence, it must be noted that recirculation of cocoa pod husk residues in the form of compost, in some cases enriched to enhance disease suppressive activity (Postma et al., 2003).

An additional observation we find between our study and other studies published in scientific literature is related to the completeness of the biogenic carbon cycle. For instance, Avadí (2023) covers the full carbon cycle of aerial and soil emissions and sequestration on fields but fails to include the emissions linked to husk decomposition on field or alternative treatment (e.g., composting). This leads to net carbon storage in the results reported, but we hypothesize that most of these negative emissions, if not all, would be neutralized when including husk treatment or spreading. In contrast, although Ivanova and colleagues (2020) exclude the treatment of cocoa pod husk or other biogenic carbon emissions or storage on field, they include the impacts of deforestation related to the expansion of the production frontier. Overall, the comparison shown in Table 10 shows multiple disparities in the activities and biogenic carbon emissions that are included in the different studies. In fact, we consider that our study fulfills a more complete and comprehensive understanding of the full carbon cycle in cocoa production.

For other impact categories, the sensitivity analysis is relevant in the case of FPMF, for which modelling transported cocoa from Satipo to Pisco shows an important difference between the baseline scenario, which assumes reported diesel consumption by trucks (i.e.,

3.96 g PM2.5eq/kg of dried cocoa beans), and the use of regular road freighting datasets per metric ton transported (i.e., 2.78 g PM2.5/kg, 30% lower), which consider average freighting conditions, and do not take into consideration the orographic and traffic conditions that can be found in the Peruvian highlands and along congested highways along the Peruvian coast (Verán-Leigh et al., 219).

When the final chocolate products are compared to the few existing full production chain studies in the literature, Boakye-Yiadom and colleagues (2021) report a GW results of 1.67 kg CO2eq/FU for a dark chocolate product with a similar cocoa content (i.e., 56%) to the products in the current study, whereas Recanati et al. (2018), with a >70% cocoa chocolate product, and Pérez-Neira et al. (2016), with a 100% cocoa bar, present GHG emissions of ca. 2.50 kg $CO_2$eq/FU. In our study we obtain similar values (i.e., 2.25-2.45 kg $CO_2$eq/FU) when the carbon balance is excluded, as the abovementioned studies do not account for biogenic emissions.

Finally, it should be noted that a series of uncertainties must be identified within the calculation framework that has been presented for Peruvian chocolate. Firstly, while there is an attempt to represent the full biogenic carbon cycle at cultivation sites, modelling limitations persist, as allometric equations were generic for non-cocoa trees. Similarly, no on-site SOC data were available, so data measured from similar conditions in Bolivia were considered. Secondly, although primary data were of relatively high quality throughout the production system, emissions were all modelled considering international or national inventory emission recommendations, although an effort was performed to include the latest and most updated versions (i.e., IPCC 2019 for $N_2O$ modelling). A third aspect to be considered is that although a detailed sample of cocoa producers was established for data collection, these do not necessarily represent average or median conditions of cocoa production in Peru.

## 5. Conclusions

The main conclusions of the current study show that organic chocolate production in Peru appears to be a low carbon option as compared to conventional chocolate production given the low amounts of materials used, namely synthetic pesticide and mineral fertilizer use, lowering the fossil-related GHG emissions. However, it must be noted that there are a few factors that affect the final environmental profile of cocoa beans production: i) carbon capture from aerial biomass at cultivation sites, both from cocoa and shading trees; ii) $N_2O$ emissions linked to the use of nitrogen-based fertilizers; iii) the accountability of fermentation emissions and, more importantly, those from cocoa pod management; iv) combustion emissions from transportation; and, v) energy and cooling agent used at the manufacturing plant.

In the first place, carbon capture has an important role in lowering carbon emissions, if shading trees are abundant in the agroforestry systems. Producers with increasted shading potential were able to produce low carbon cocoa beans provided they also employed other low-carbon practices. In contrast, producers with no shading trees showed recurrently higher GHG emissions.

Secondly, nitrogen-based fertilizers have been identified as significant contributors to final GW results. Considering the organic characteristics of the fertilizers applied, production-related emissions are lower than mineral fertilizers, which also contributed to lower GHG emissions and low-carbon values. However, $N_2O$ emissions constitute an important source of GHG emissions in the production system due to the application of nitrogen fertilizers. The use of recent IPCC models, with a higher level of granularity, that allow modeling wet tropical conditions rather than a more generic model, have proven to more accurately represent GHG emissions linked to fertilization, showing lower emission factors than when modelling is conducted with previous models. Although IPCC 2019 is a recognized reliable method for assessing these emissions, a major limitation still resides in the fact that scientific literature on $N_2O$ emissions relies on limited primary data, so specific local conditions cannot be considered with current $N_2O$ models and LCA software.

A third issue is the management of cocoa pod residues, as these appear to be crucial parameters when untreated. A simple decomposition of these pods at cultivation sites can increase total GHG emissions up to ten-fold due to the higher methane emissions. However, in the sample we worked with, producers had already implemented partial composting systems to treat between 25% and 75% of total residues. Hence, at this point a critical climate action initiative in cocoa production would be to increase the rates of cocoa pod composting, as well as ensuring that composting occurs under the most optimal conditions (e.g., ensuring stability and maturity of the compost) to avoid fugitive methane emissions. In fact, the low-carbon scenario demonstrates that optimal and universal composting of cocoa pods would lower GHG emissions to ca. 0.09 kg $CO_2$eq per kg of dried cocoa beans.

A positive result obtained in this study is the fact that certain producers, provided that they yield reasonable amounts of cocoa beans and have sufficient shading in their allotment, will actually sequester more carbon than they emit in their system as long as cocoa pod residue management is treated under adequate composting conditions. However, when current conditions are modeled, this scenario is still far away, as untreated cocoa pod residues elevate the carbon footprint of cocoa beans to over 5 kg $CO_2$eq/kg for all producers. In contrast, extending controlled composting to all residues, and augmenting the number of shading trees at the cultivation site, prioritizing species with increased carbon capture potential, although not always feasible, can take these cultivation sites (close) to carbon neutral conditions.

A limiting factor to these GHG emissions, however, is the fact that the most meaningful GHG emissions are linked to $N_2O$ emissions on field and methane emissions in the treatment of on-field organic residues. Hence, beyond LCA modelling we recommend that on field emissions should be measured for these processes to validate modelling standards used in the current study.

A final aspect in terms of carbon emissions is transportation and manufacturing. Most transport in Peru occurs at low speeds due to either congested roads or orography. In the case of transportation of dried cocoa beans to the plant along the Peruvian coast, this must travel across mountain passes in the Andes, elevating the fossil fuel intensity of the trip, and, therefore, carbon emissions, as well as other impact categories, such as human toxicity and FPMF. There are limited resources that can be applied to improve the existing infrastructure from a company perspective; however, alternatives can include the optimization of cocoa bean loads from Satipo to Pisco, or the future inclusion of electric lorries in a country with low-carbon electricity emissions. Regarding the production of chocolate, the production of sugarcane is another important source of environmental impacts, even though the high cocoa content of the products assessed lowers its relative weight. Moreover, electricity production, the use of cooling agents, and water use are the main environmental hotspots to be addressed in this stage.

Further research should focus on coupling LCI data with direct measurements at the cultivation sites, particularly for methane and nitrous oxide emissions. In addition, the expansion of the environmental assessment towards new environmental pathways in LCIA, such as the damage of plastic emissions, or the impact on biodiversity, may provide new decision-making challenges for the chocolate industry.

## Declaration of competing interest

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

The study has been mostly funded by Riverside Natural Foods Ltd., a food manufacturing company specializing in natural and organic snacks. However, the authors declare that neither these nor any other interests have directly or indirectly influenced the objectivity of this paper, and the findings and conclusions in the paper are those of the authors alone, independent of their organizations or funding sources.

## Data availability

Data will be made available on request.

## Credit author statement

**Ian Vázquez-Rowe:** conceptualization, investigation, validation, resources, writing (original draft), supervision, funding acquisition, project administration; **Patricia Mogrovejo:** methodology, validation, formal analysis, investigation, writing (original draft); **Eizo Muñoz:** methodology, formal analysis, investigation, software; **Pablo González-Socorro:** methodology, formal analysis, writing (review and editing); **Karin Bartl:** methodology, formal analysis, writing (review and editing); **Isabel Quispe:** conceptualization, formal analysis, writing (review and editing), supervision, funding acquisition; **Jhonnatan Murga:** validation, supervision; **Shenali Madhanaroopan:** supervision, writing (review and editing); **Salma Fotovat:** validation, supervision, funding acquisition; **Taylor Stanley:** conceptualization, supervision, funding acquisition, writing (review and editing).

## Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors did not use any sort of Generative AI and AI-assisted technologies in the writing process.

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**Declaration of competing interest**

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