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ABSTRACT

Consumers are increasingly interested in knowing the environmental impacts of foods. In addition, producers are interested in receiving recommendations to reduce their impacts. This faces two major challenges: (1) certain systems are not widely studied and (2) not all production stages are included in system boundaries (e.g. only the agricultural stage or the supply chain). Life Cycle Assessment was applied to a specific small-scale and low-input organic apple value chain. The system boundaries included the cultivation, processing and distribution. All transport and waste management were considered. The main contributors to environmental impacts are: cultivation, juice and applesauce production, retail and consumption. Compared to literature, cultivation is efficient. Processing and retail are respectively influenced by the use of glass packaging, the cold storage of fresh apples and the transport to stores. Consumption was influenced by the management of apple waste and the consumer trip. Literature survey and results confirm that the system was not represented in the literature and provides new insights into the entire value chain, as well as new proxy LCIs. Similar specific studies should be repeated in the future to cover the variability. It is an essential step towards applying the environmental footprint fairly to alternative systems.

1. Introduction

1.1. General introduction

Due to growing societal concerns, the food sector is constantly changing, and at every stage of the food value chain. Agricultural systems that use fewer chemicals and produce less emissions are promoted (Tscharntke et al., 2012). For processing, efficiency is increased, and all ways to extract value from waste and by-products are explored and encouraged. For distribution, new packaging solutions are developed, and logistical chains – especially those with new challenges – are increasingly examined (Mittal et al., 2018). Finally, for consumption, diets based on fewer animal products are promoted (Poore and Nemecek, 2018), and combining relocation of production with a decrease in the number of intermediaries in the supply chain is frequently cited as a way to positively act through consumption (Chiffoleau, 2019). In addition, efforts are placed on decreasing food waste and on collecting and using what waste does remain (Zaman, 2015).

In this context, "alternative" farmers have looked beyond maximising economic profit alone to include societal and environmental considerations in their production systems (Morel and Léger, 2016). These systems, often re-discovered and adapted from ancient practices, include several societal values in their development, such as preservation of natural resources, revitalization of a territory, access to good and healthy products and equity among people, all of which help improve the quality of life (Lamine and Chiffoleau, 2016). Some examples of alternative farming systems include micro-farms, farmer-bakers and farmer-brewers. Including societal values goes hand in hand with

Abbreviations: LCA, Life Cycle Assessment; LCI, Life Cycle Inventory.

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choosing partners who share similar views. Alternative systems cannot focus only on the agricultural stage; instead, they usually consider the entire value chain (Meynard et al., 2017). In addition, this holistic perspective is also a way to keep control of the sharing of economic value within the value chain (Alonso Ugaglia et al., 2020).

Environmental protection is one objective of alternative systems; however, their environmental impacts are rarely demonstrated. When they are, Life Cycle Assessment (LCA) is one of the methods used most. LCA is a methodological framework for quantifying environmental impacts of a products or a service, all along its life cycle (multi-stages), covering several environmental issues (multi-indicators) (JRC and International, 2010). It is widely applied in the agri-food sector (Curran, 2015; Basset-Mens et al., 2022). LCA has been widely applied to organic agriculture, with contrasting results depending on methodological choices. Some gaps have been identified, such as difficulty considering certain key issues (e.g. biodiversity) and additional functions of the system (e.g. ecosystem services) (van der Werf et al., 2020), or the lack of Life Cycle Inventories (LCIs) or inputs specific to organic agriculture (Montemayor et al., 2022). The wide range of agricultural systems that exist between alternative and intensive farming add to the complexity of producing assessments that represent all types with standard methods. For example, in an LCA of vegetable production, Pépin et al. (2021) argue that organic vegetable farms should be considered on a gradient from "agroecological" to "conventionalized" (Pépin et al., 2021). In addition, Mouron et al. (2006) conclude that choosing the apple with the lowest environmental impacts depends not only on its production (integrated vs. organic) but on a strong understanding of the entire system and its management (Mouron et al., 2006). As consequence of the variability and the need to enlarge system boundaries to the entire agri-food chain, some alternative systems studied in the LCA literature suffer from a lack of representativeness and comprehensiveness.

1.2. State-of-the art of LCA studies applied to apple value chains

This study focused on apple cultivation and use. Apples, one of the most widely produced fruits in the world (FAO, 2020), and consumed in Europe (Konopacka et al., 2010). LCA has been applied mainly to apple cultivation, making it the fruit whose environmental impacts have been studied most (Clune et al., 2017). In a review, apple cultivation was used to show the relevance of LCA as a method to assess environmental impacts of perennial crops and identify its gaps (Bessou et al., 2013). In many studies, LCA is used to compare diverse types of apple cultivation, such as conventional vs. organic (Reganold et al., 2001; Alaphilippe et al., 2013; Keyes et al., 2015; Goossens et al., 2017; Longo et al., 2017; Ingrao et al., 2018; Zhu et al., 2018). While most environmental impacts are lower under organic production, the results vary greatly, as they depend strongly on methodological choices, such as the functional unit (Cerutti et al., 2013). In their study, Cerutti et al. (2013) showed that Golden Delicious apple variety involved less environmental impacts than ancient cultivars when considering a mass-based functional unit when ancient cultivars were environmentally better with area-based and income-based functional units. Other apple-production practices have been compared: an intensive vs. semi-extensive apple orchard, showing higher impacts for the former, mainly due to fertilization (Alaphilippe et al., 2016); conventional vs. low-carbon apple cultivation, demonstrating environmental benefits of a low-carbon strategy (Kim et al., 2020) and heirloom vs. current varieties, concluding that the ranking depends strongly on the functional unit considered (Cerutti et al., 2013). Two studies found that apples had lower environmental impacts than other fruits (Basset-Mens et al., 2016; Svanes and Johnsen, 2019). Two other studies compared imported fruits and vegetables (including apples) to similar national products from the United Kingdom (UK) and highlighted the large contribution of transport, which resulted in a recommendation to British consumers to buy local and seasonal products (Sim et al., 2006; Jones, 2002). Most comparisons set the system boundaries from the cradle to the farm gate, which is consistent with the objective to compare agricultural systems (Supplementary Materials 1). Some studies extended the boundaries to the storage gate (Alaphilippe et al., 2016; Naderi et al., 2020), the retail gate (Keyes et al., 2015; Zhu et al., 2018), or the consumer's household (Longo et al., 2017; Svanes and Johnsen, 2019). Large contributions have been found for post-harvest stages, especially due to energy consumption for cold storage of apples. Finally, Loiseau et al. (2020) compared apple supply chains in detail (using the same apple cultivation for all scenarios), showing that short food supply chains do not always have lower environmental impacts, due to high variability within each of the scenarios. For example, consumers' trips to purchase apples have a large contribution and can vary in distance, the weight of the apples purchased, its percentage of the total purchase weight and transport mode. This result encourages us to work to identify parameters that can improve specific supply chains rather than try to identify the best supply chain (Loiseau et al., 2020).

LCA can also provide contribution analysis, which identifies which stages contribute most to impacts throughout the life cycle. LCAs of apple cultivation show large contributions of fertilization and mechanical operations (especially for organic production, which partly offsets its use of fewer pesticides and fertilizers). Bamber et al. (2020) did not recommend using mulch in apple orchards when applying using attributional LCA, which estimated higher impacts of mulch (Bamber et al., 2020), but their consequential LCA produced inconclusive results when considering other uses of mulch (Bamber et al., 2021). Expanding the boundaries to the entire value chain allows other sources of impact to be identified. Keyes et al. (2015) highlighted the large contribution of electricity (especially coal-based) to store apples. Longo et al. (2017) and Boschiero et al. (2019)also found a large contribution of post-harvest stages (mainly packaging and storage) and of transport. Svanes and Johnsen (2019) also showed a large contribution at the consumer's household by considering the proportion of the apples wasted. Iriarte et al. (2021) used LCA to estimate the carbon footprint of Chilean apples imported into the UK. They estimated a large contribution (ca. 40%) of all transport stages, especially ocean freight. Two published LCAs studied processing of apples into apple juice, but they differed from our study. The first concerned industrial production of conventional apple juice in polyethylene bottles (Khanali et al., 2020), while the second concerned production of concentrated apple juice in China without including packaging (Cheng et al., 2022). Both showed that apple cultivation contributed the most to impacts, due to the use of pesticides and fertilizers. To our knowledge, the literature contains no LCA of applesauce. Only one LCA of peach compote was found, which showed little contribution of the cultivation phase (Nanaki and Koroneos, 2018).

Several major points can be extracted from the literature: (1) apple production systems show variable environmental impacts (Fig. 10); (2) some systems lack representative LCA results, notably to cover the range of organic systems; (3) apple systems in particular lack such results, especially when considering the entire value chain; and (4) small-scale apple juice and applesauce production have not been studied using LCA. Based on the identified literature gaps, the research goals of this study are to (1) participate in the description of the variability in apple production systems and their related environmental impacts and (2) enlarge the scope to the whole value chain including processing stages.

Towards these objectives, our case study orchard used varieties adapted to the geographical context with small-scale and low-input organic practices. Some of the apples were processed into juice and applesauce, most of which were sold locally. In addition, as he reported during the interview, the farmer set societal criteria as main drivers (e.g. employment on the farm, processing into applesauce at a small-scale processing facility that employed disabled workers) and had objectives of improvement for the future (e.g. reusable bottles for juice, new packaging for applesauce). This study aimed to identify environmental impacts of the value chain to help the farmer prioritise future developments. As a secondary added-value, this study also developed an

LCI for a non-conventional apple cultivation and processing system and LCA results for this system. As non-conventional systems vary greatly, this study cannot represent the entire category. However, the results were analysed and explained in light of the literature. The need for additional LCAs of non-conventional systems, in a context where they are increasingly expected, is discussed.

2. Materials and methods

2.1. Case study

The orchard studied is located in French Flanders (Nord department in France), near the border with Belgium. Its mean annual temperature is 11 °C, mean annual precipitation is 741.4 mm and mean annual hours of sunshine is 1628 h (www.lameteo.org). For the production year studied, the orchard produced 50 t of organic apples – mostly the Boskoop variety – on 3 ha. The trees had a density of ca. 1125 trees/ha and a lifespan of ca. 25 years. Most of the apples (grade 1 and 2 calibrated at the fruit cooperative) were sold fresh during the year, which required cold storage at the cooperative. The rest were processed into juice at the cooperative and applesauce at a local assisted employment center that employ disabled people, and then sold locally.

2.2. LCA methodology

We followed the four methodological steps of LCA (ISO and ISO-14040:2006, 2006; ISO and ISO 14044:2006, 2006): goal and scope definition (i.e. objectives, geographical and temporal boundaries, functional unit and system boundaries), LCI, Life Cycle Impact Assessment (LCIA) and interpretation.

2.2.1. Goal and scope definition

The objectives of the study were to (1) produce an LCI for a low-input and small-scale production of organic apples in French Flanders, including processing into juice and applesauce; (2) estimate its environmental impacts and the relative contributions of each stage, to help the farmer make further improvements and (3) discuss LCA of non-conventional systems and introduce options to test to improve the value chain in the future. Given these objectives, an attributional approach was chosen.

2.2.2. System boundaries and functional unit

The system boundaries included all life cycle stages from the cradle to the grave, divided into three main phases: agricultural production (i.e. cradle to farm gate from one single farm), processing (i.e. farm gate to retail) and retail and consumption (i.e. retail to grave). Agricultural production included cultivation of apples from the tree nursery to the harvest of the apples (including field operations and additional materials). Processing included sorting of fresh apples (calibration) and their storage until they left the cooperative for retail stores. It also included the processing of downgraded fruits into juice and applesauce (processing and packaging). Finally, retail and consumption included transport of the three final products, their retail and their use by consumers (including waste management).

The functional unit was defined as "the orchard's annual production of fresh apples, juice and applesauce delivered to consumers". The impacts of each of the three products were also calculated individually using mass-based functional units for potential future scientific uses. This is not detailed in this paper as considered out of the scope of the study. See the associated data paper for details on allocations and numerical values.

2.2.3. Life cycle inventory

Most foreground data were collected during an interview with the farmer (one single farm), in 2022. The Agribalyse 3.0 and ecoinvent 3.8 databases were used for background data. See the associated data paper and dataverse (https://doi.org/10.57745/SA0IXW) for all LCI data and more details about their collection and calculation. The main information is summarized here.

The farmer indicated that 25-year-old trees still had good yields; so, he planned to extend their lifespan. In the absence of prospective data, a lifespan of 25 years was used in the LCI, which is consistent with the literature. To prevent diseases (e.g. scab caused by *Venturia inaequalis*, powdery mildew caused by *Podosphaera leucotricha*), a combination of sulphur and potassium bicarbonate was spread on the field. Related emissions were estimated using the INRAE MEANS InOut platform (https://www6.inrae.fr/means). Aphids were fought by conserving natural predators (i.e. earwigs) and spraying neem oil when necessary. Codling moths were fought by diffusing pheromones to cause selective sexual confusion. Weeding was performed mechanically with a small tractor (i.e. 60 horsepower equivalents to 44.12 kW). Three 4-day interventions, adapted to conserve earwigs, were necessary to weed the entire orchard. As a former pasture for many years, the orchard's soil had a high organic matter content and required no additional fertilization (then no direct emissions related to fertilization such as N_2O). These nutrients were considered burden free in the baseline scenario. Finally, the orchard was not irrigated. Apples were harvested manually by seasonal workers using stepladders and stored in wooden bins (pallet bin). Each pallet bin, estimated to last 25 years, can hold 300 kg of apples. As an initial approach, a pallet bin was assumed to consist of 5 wooden pallets. To avoid double counting, pallet bin impacts were grouped with the transport of apples from the orchard to the cooperative, not with the cultivation stage.

After harvesting, apples were transported in pallet bin to the cooperative, 3.5 km from the orchard, where they were calibrated. Of the 50 t produced, 38.45 t were sold fresh and 11.05 t and 0.5 t were processed into juice and applesauce, respectively. Juice was flash pasteurized at 80 °C, and applesauce was warm filled after processing with no further heat treatment. In total, 5.5 L of water were used to produce 1 L of juice (mainly for cleaning, followed by cleaning agents). We assumed that the same amount was used to produce 1 kg of applesauce. Fresh apples were cold stored at the cooperative and progressively sent to retail during the year. In total, 6500 L of apple juice were packaged at the cooperative in glass bottles, with aluminium caps and polypropylene labels. In total, 250 kg of applesauce were produced at a workshop covered factory 10 km from the cooperative, to which apples were transported by light commercial vehicle. The applesauce was packaged in 250 g glass jars. Pomace from juice (4550 kg) and applesauce (125 kg) production were sent to anaerobic digestion (AD).

Fresh apples were sold in organic stores throughout France, but most of them remained in the area where they were produced. Juice and applesauce were sold locally in a 30 km radius around the orchard. Only fresh apples consumed energy at retail due to cold storage. Based on the literature (Loiseau et al., 2020), we assumed that 5% of fresh apples were lost at retail.

Transport from the store by consumers was included by using the farmer's estimates of market shares and some literature data. In the consumption stage, the end-of-life of packaging materials was considered, as was apple waste. The current French mix of biowaste-treatment solutions was used. Consumers were assumed to store only juice and applesauce in the refrigerator.

2.2.4. Life Cycle Impact Assessment

The LCIA was performed using the EF 3.0 (adapted) characterization method (Fazio et al., 2018) and SimaPro 9.3.0.3 (PRé Sustainability, Amersfoort, Netherlands). All 16 impact categories of EF were considered: Climate change (CC), Ozone depletion (OD), Ionising radiation (IR), Photochemical ozone formation (POF), Particulate matter (PM), Human toxicity, non-cancer (Tox-nc), Human toxicity, cancer (Tox-c), Acidification (Acid), Eutrophication, freshwater (Eut-F), Eutrophication, marine (Eut-M), Eutrophication, terrestrial (Eut-T), Ecotoxicity, freshwater (Ecotox-F), Land use (LU), Water use (WU), Resource use, fossils (Res-F) and Resource use, minerals and metals (Res-M). In some studies, practitioners justify to select categories that are relevant for the purpose (e.g. eutrophication for agricultural systems). In this study, it has been chosen to keep all the impact categories as the system boundaries includes steps that could involve to various impacts (e.g. eutrophication for cultivation phase, particulate matter for transports or ionising radiation for processing).

2.2.5. Sensitivity analysis

The farmer indicated that no fertilizer had ever been applied, as the orchard benefitted from the previous use of the field as pasture, which had enriched the soil in organic matter. This absence of fertilization is uncommon in the literature and can be questioned for two reasons. First, the presence of grazing cattle in the past could be considered equivalent to the supply of organic matter at planting. Second, it is difficult to estimate how many years the non-fertilization strategy would remain viable, as apple cultivation progressively removes nutrients from the soil. Thus, two sensitivity scenarios were tested: the same production with (1) application of cattle manure (25 t/ha) during the first year or (2) land preparation and nutrient management derived from Keyes et al. (2015). See the associated data paper for the data used.

Whether and how to consider carbon sequestration is a recurrent issue in LCA. Perennial crops such as apple orchards assimilate carbon during their lifespan that is stored in biomass. Unlike the orchard's main ecosystem service (i.e. to produce apples), this additional service is usually excluded from LCA (Bessou et al., 2013). The exclusion is rarely justified by the lack of data (Svanes and Johnsen, 2019) or the temporal horizon during which the soil carbon content is assumed to remain constant (Vinyes et al., 2017). To be able to compare our results to those in the literature, this study did not include carbon sequestration in the baseline scenario, but did study and discuss it in a sensitivity analysis. It addressed two questions: (1) How much carbon does the orchard sequester in its biomass during its lifespan? and (2) What is done with tree biomass after pruning or at the end of the orchard's lifespan? The carbon sequestered by the trees was estimated using allometric equations developed in a recent study (Sangines de Carcer et al., 2022). Concerning the fate of the trees, three scenarios of wood use were compared: (1) burnt on site, which re-emits the stocked carbon without providing an additional service; (2) used as firewood, which avoids production of biofuel elsewhere (system expansion) or (3) used as mulch (system expansion). See the associated data paper for the data used.

A large amount of apple waste is produced throughout the value chain. This study considered the apple waste produced when processing juice and applesauce (sent to AD), during the retail stage and at home by consumers. For the latter two, the French mixture of biowaste management methods was used and modelled as LCI to assess impacts. However, biowaste management is an evolving issue, especially in recent years. Generalizing biowaste sorting is an objective for 2024 in France, and many experiments for doing so are already underway. The objective is to collect 100% of biowastes separately and to divide them among individual/collective on-site (i.e. home) composting, industrial composting and AD. To consider this change, a sensitivity analysis was performed for biowaste management using prospective mixtures. In the absence of technical data, two main parameters were considered in six scenarios: separate collection efficiency (50% or 100% of waste collected) and the percentages of the three management methods. The analysis focused on impact categories that had large differences between scenarios (i.e. $\geq$ 5% between worst and best). See the associated data paper for details. Finally, as mentioned, the farmer planned to increase the lifespan of apple trees beyond 25 years. This increase was tested in the sensitivity analysis, but it did not influence the results strongly; thus, it is not presented.

3. Results

3.1. Results of the LCIA

This section describes the main results of the LCIA. More details on numerical values are available in the associated datapaper (see Fig. 1).

3.1.1. Overall assessment

Four main stages within the system boundaries contributed most of the environmental impacts: cultivation of apples, processing and bottling of juice, retail of the products and consumption (Fig. 2).

The cultivation stage contributed 9% (WU) to 93% (LU) of total impacts. Ecotox-F was influenced mainly by direct emissions (i.e. sulphur that enters the soil after being used to prevent diseases) (Fig. 3). Phosphate emitted to water during the cultivation stage contributed greatly (i.e. > 25%) to Eutro-F. For the other categories, impacts during the cultivation stage were related directly to mechanical operations (i.e. weeding and using a tractor to spread manure) and more specifically diesel combustion. Thus, Eutro-M, Eutro-T, POF and Acid were due mainly to emission of nitrogen oxide, while CC was due mainly to emission of carbon dioxide. Res-F was due mainly to consumption of crude oil. Finally, the metal in the tractor was the main contributor to Res-M.

The juicing stage, which included pressing of fresh apples and bottling (including packaging), contributed 3% (Ecotox-F and LU) to 69% (WU) of total impacts (Fig. 4). This was due mainly to the use of glass bottles, which contributed 29% (WU) to 93% (LU) of the impact, and less than 75% for only two categories: WU, due to direct consumption of water and IR, due to electricity use. The use of aluminium also contributed strongly to Eutro-F (20%) and to toxicity-related impacts (11%, 9% and 9% for Tox-c, Tox-nc and Ecotox-F, respectively). Finally, treatment of apple pomace by AD contributed to CC (10%) and Ecotox-F (11%).

Contributions of the retail stage ranged from 1% (Ecotox-F) to 19% (IR) of the total impacts (Fig. 5), due mainly to transporting final products to stores, especially fresh apples (by 16–32 t lorry throughout France) and juice (by a light commercial vehicle to local stores). Although more fresh apples than juice were transported (by mass), the transport of fresh apples did not contribute much more than that of juice. This was due to the higher relative impacts of light commercial vehicles, which are less optimized than 16–32 t lorries, which benefit from an economy of scale. Except for transport, the retail stage was influenced by the need for cold storage of fresh apples before shelving, which contributed strongly to IR (81%) and resource-use categories (i.e. WU, Res-F and Res-M).

Contributions of the consumption stage ranged from 1% (LU) to 35% (HT-c) of total impacts, due mainly to transporting the three products from stores to the consumer's household, mainly by automobile (Fig. 6). It was also related to waste management, especially biowaste management, which contributed strongly to all impact categories. Finally, cold storage at home contributed strongly to IR (16%).

Besides the contribution of these four main stages, other stages had large contributions for specific impact categories. IR was strongly influenced (39%) by electricity use (cold storage of fresh apples at the cooperative, followed by calibration). Despite the small amount of applesauce produced, applesauce processing and packaging contributed 3–4% of total impacts (except for not contributing to Ecotox-F or LU). Like impacts of the juice, those of the applesauce were related mainly to using glass packaging.

3.2. Sensitivity analysis

3.2.1. Sensitivity analysis of fertilization

Changes in fertilization increased impacts by different percentages among the impact categories. It was especially high for Acid, Eutro-F and Eutro-M, which increased by ca. 85%, 75% and 60%, respectively,

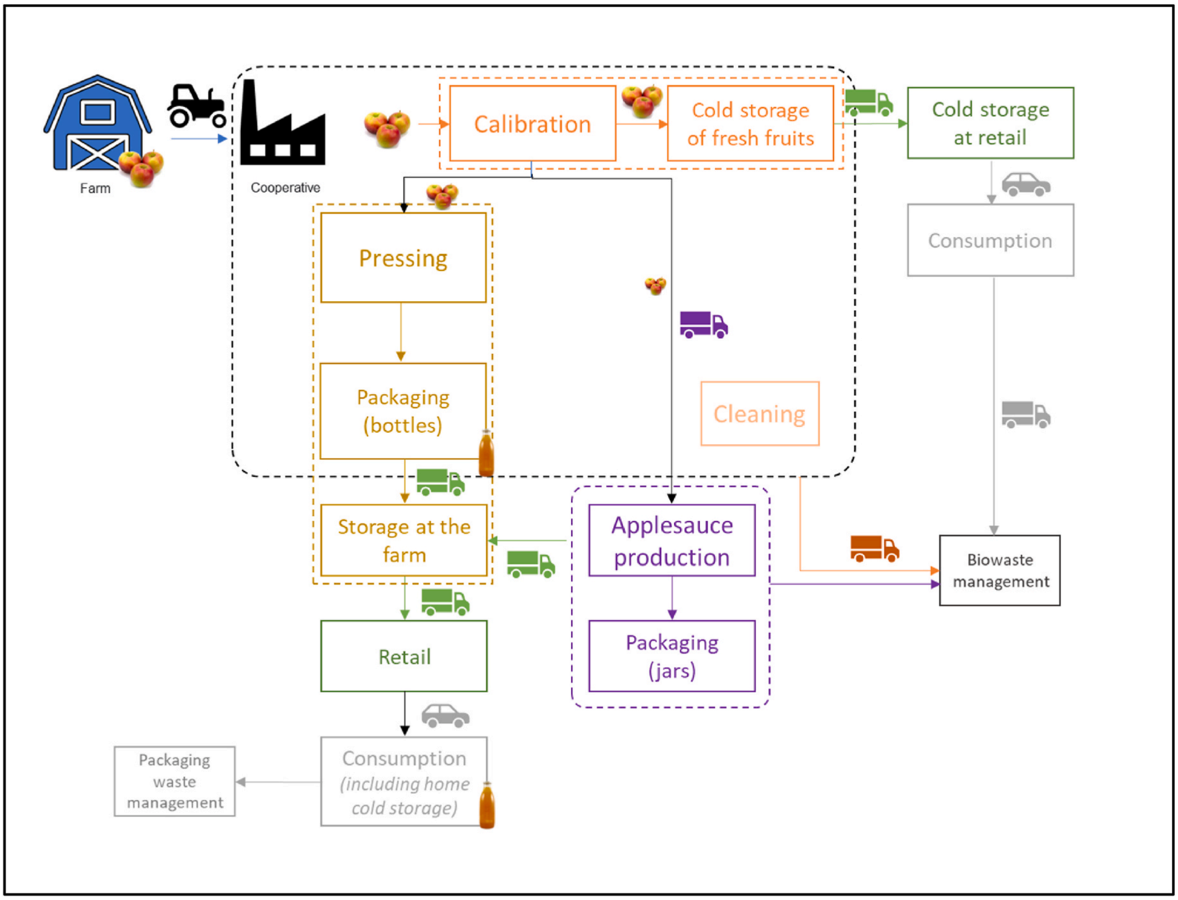

Fig. 1. Simplified flow diagram of the system studied from the cradle to the grave (apple cultivation from the cradle to farm gate is not detailed).

between the baseline scenario and land preparation and nutrient management derived from Keyes et al. (2015) (Fig. 7). The increase was smaller for WU (30%) and CC, POF and Res-F (ca. 20%). These results were consistent with those of Keyes et al. (2015) for contributions to impacts of apple cultivation. When considering the entire life cycle (from the cradle to the grave), the scenario based on Keyes et al. (2015) had much higher impacts for Acid (+168%), Eutro-F (+69%) and Eutro-M (+67%). Some impact categories in the sensitivity analysis were difficult to interpret due to high uncertainty (e.g. applying cattle manure during the first year resulted in a large negative impact for HT-c due to a large negative amount of heavy metals in the soil, as heavy-metal dynamics are subject to high uncertainty (Koch and Colomb, 2015)) See Supplementary materials 2 and 3 for details about the data used and full results.

3.2.2. *Sensitivity analysis of biomass management at the orchard's end-of-life*

Carbon sequestration is a crucial issue as it is an important mechanism for mitigating climate change. Assessing its potential benefits, however, faces major methodological issues related to temporality. Sequestering carbon in trees benefits short-term objectives to reduce greenhouse gas emissions, but its middle- and long-term influence on CC depends on how the biomass is managed when the orchard is destroyed. If the biomass is burnt, the carbon will be released and will contribute to CC. In other cases, some (e.g. use of wood as mulch) or all (e.g. use of wood for manufactured products) of the carbon will remain sequestered longer. Nevertheless, the temporality issue is crucial, as it is not cutting the tree to produce wood that sequesters carbon but its growth over time. For those reasons, we focused the sensitivity analysis on biomass management at the orchard's end-of-life, assuming in all scenarios that the carbon sequestered in the orchard would be re-emitted. Nevertheless, as the biomass can provide additional services, it could help avoid external production. The avoided impacts were thus those caused by producing an equivalent amount of (b) firewood or (c) mulch. The avoided impacts were high for all impact categories, especially for Eutro-F (14%) and POF (22%), representing more than half of the impacts related to production (Fig. 8).

3.2.3. *Sensitivity analysis of biowaste management*

Varying biowaste management to reflect upcoming regulations decreased CC and Eutro-M by a similar percentage regardless of the scenario (ca. −10% and −15%, respectively) (Fig. 9). It also decreased Eutro-F, especially when the collection was 100% efficient (ca. −11%). Results were less conclusive when the collection was only 50% efficient. Finally, impacts tended to increase Acid in the scenarios that favoured industrial composting, as a function of its percentage.

4. Discussion and perspectives

4.1. *Comparison to previous studies*

4.1.1. *Focus on climate change from the cradle to the farm gate*

As mentioned, the study did not aim to compare this system to others. To be most accurate, LCAs should be compared only if they have similar methodological approaches (e.g. system boundaries, functional unit). Furthermore, comparison can only be partial, as other studies do not necessarily consider the same impact categories. Nevertheless, it is important to compare results to those from the literature to assess their overall consistency and attempt to explain possible differences. Furthermore, even though the objective was not to draw general

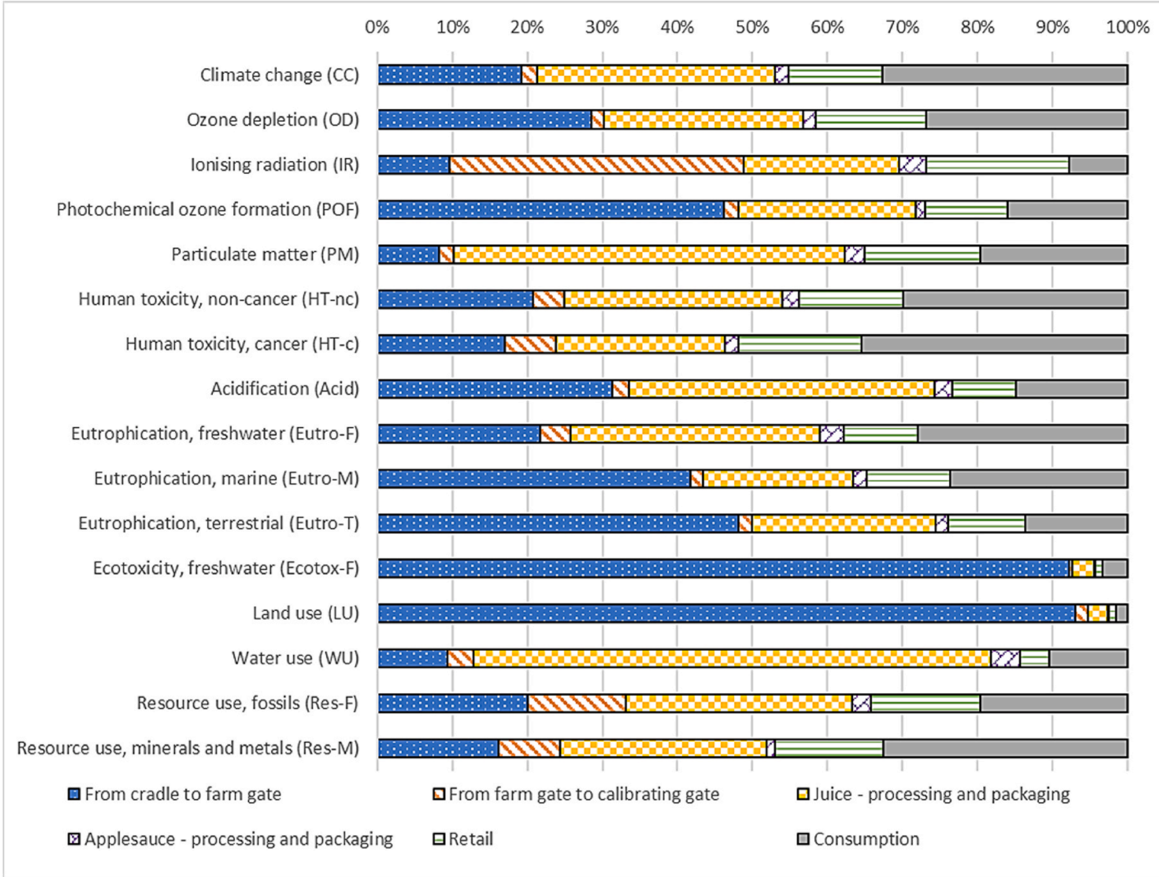

Fig. 2. Contribution of life cycle stages to environmental impacts.

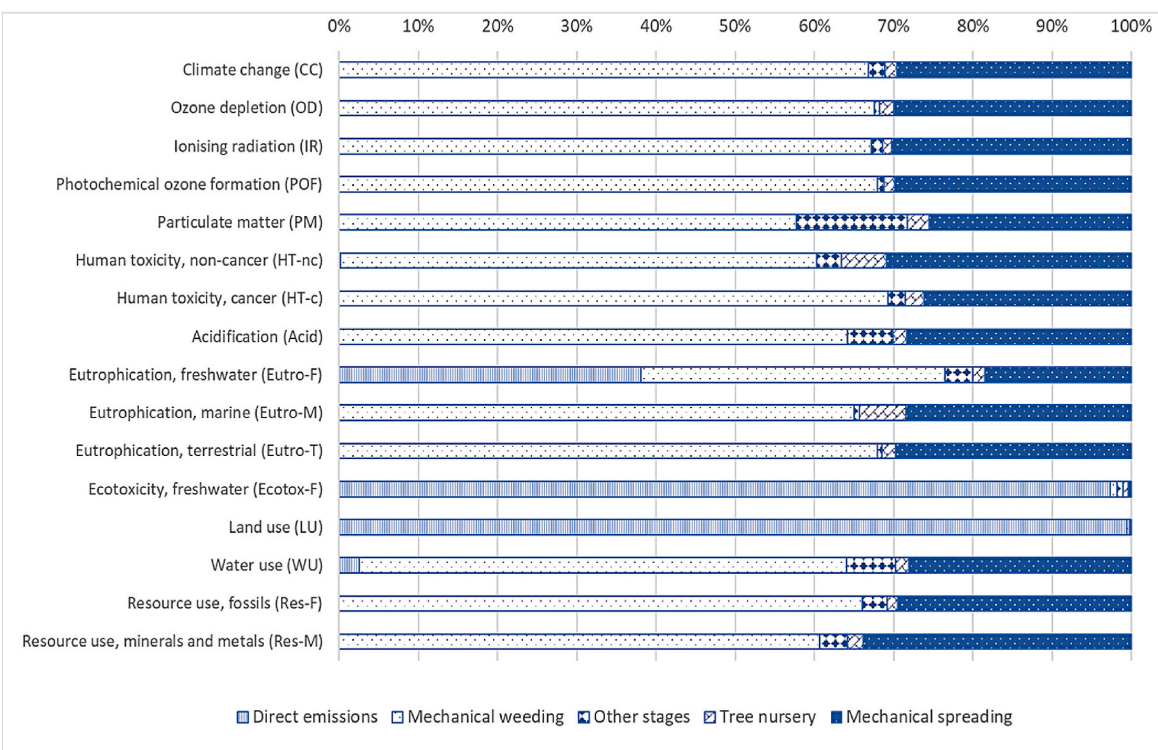

Fig. 3. Contribution analysis from the cradle to the farm gate (i.e. cultivation stage).

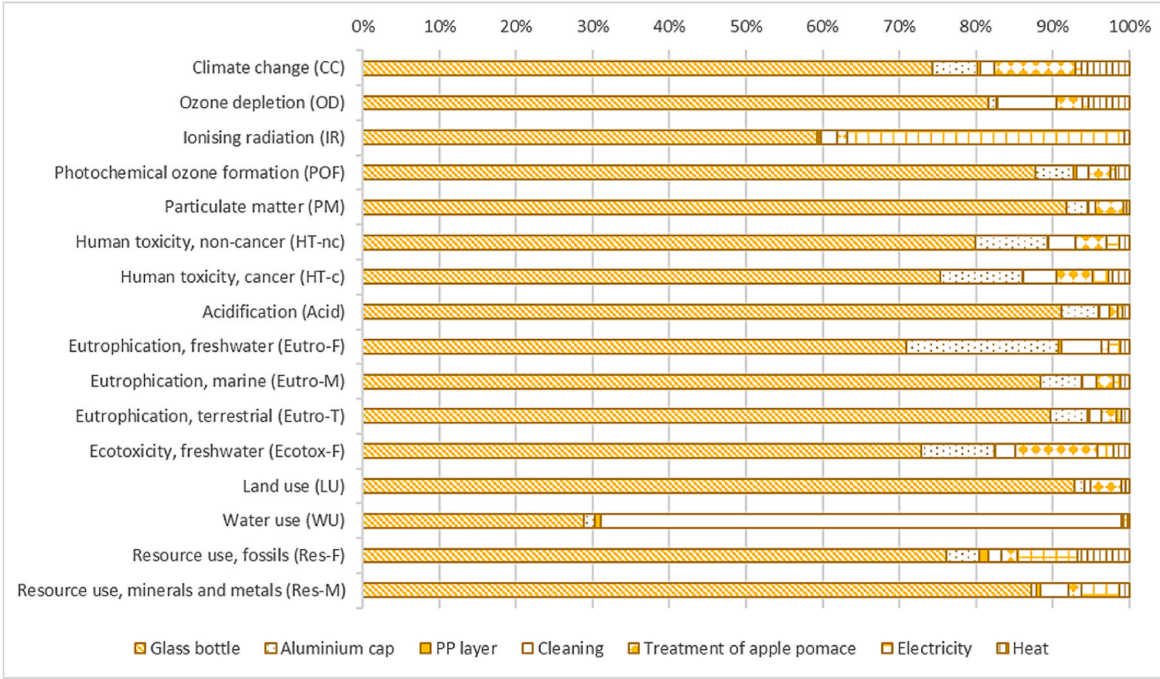

Fig. 4. Contribution analysis of the processing and packaging of apple juice. PP: polypropylene.

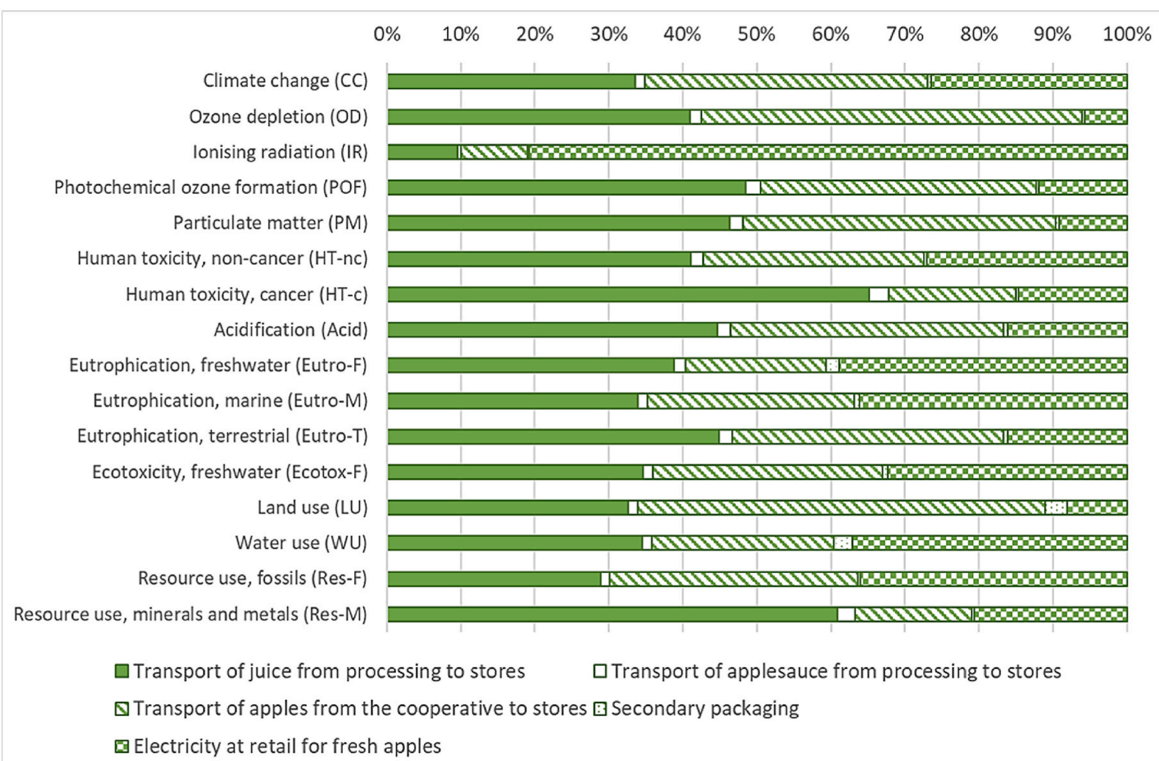

Fig. 5. Contribution analysis of the retail stage.

conclusions (e.g. about low-input organic production), some initial insights could be obtained. We first focused on comparing CC, which is the most common impact assessed in the literature and also the one with the most consistent characterization factors and units. In contrast, eutrophication can be assessed as 1–3 impact categories and expressed in a variety of units depending on the characterization method, which makes comparisons difficult. We found 23 studies of apple cultivation (Supplementary materials 1) that had estimated CC impacts per kg from the cradle to the farm gate (Fig. 10). The system in the present study was located below the first quartile, which indicates that its CC impact generally agrees with those in the literature and was relatively low. This is not surprising, and can be explained in relation to discussions in the literature, in which CC impact is usually caused by two main contributors: diesel use by mechanical operations (Milà i Canals et al., 2006;

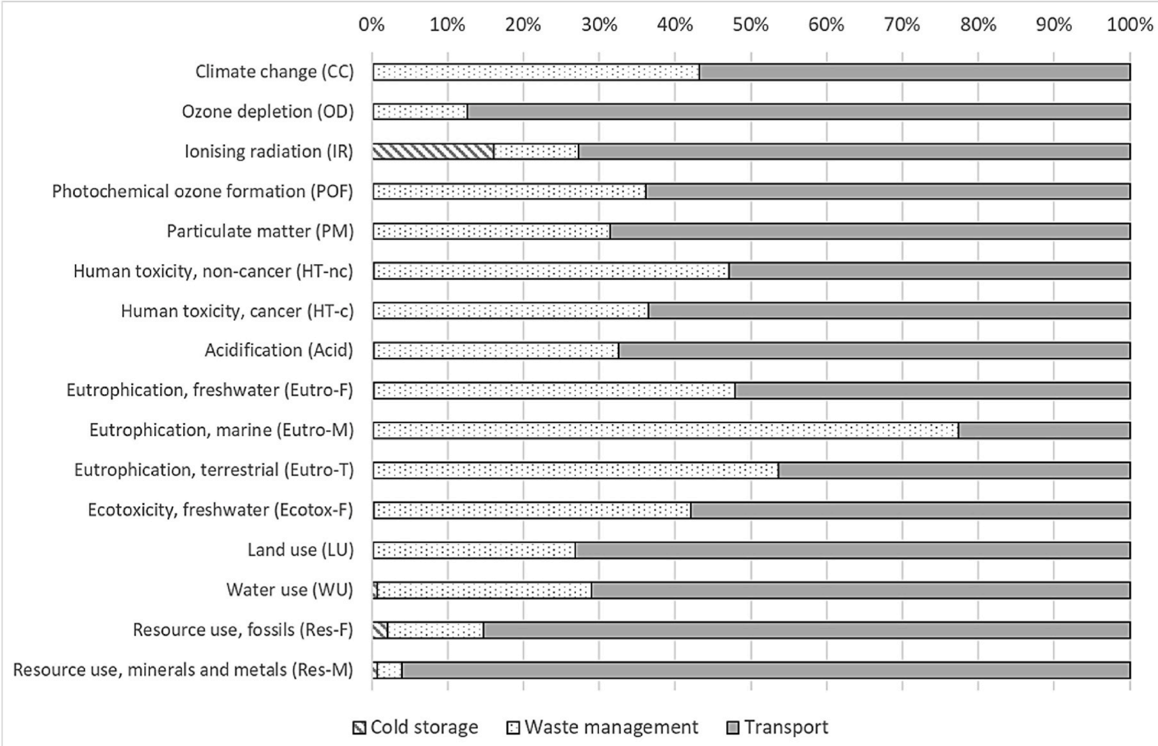

Fig. 6. Contribution analysis of the consumption stage.

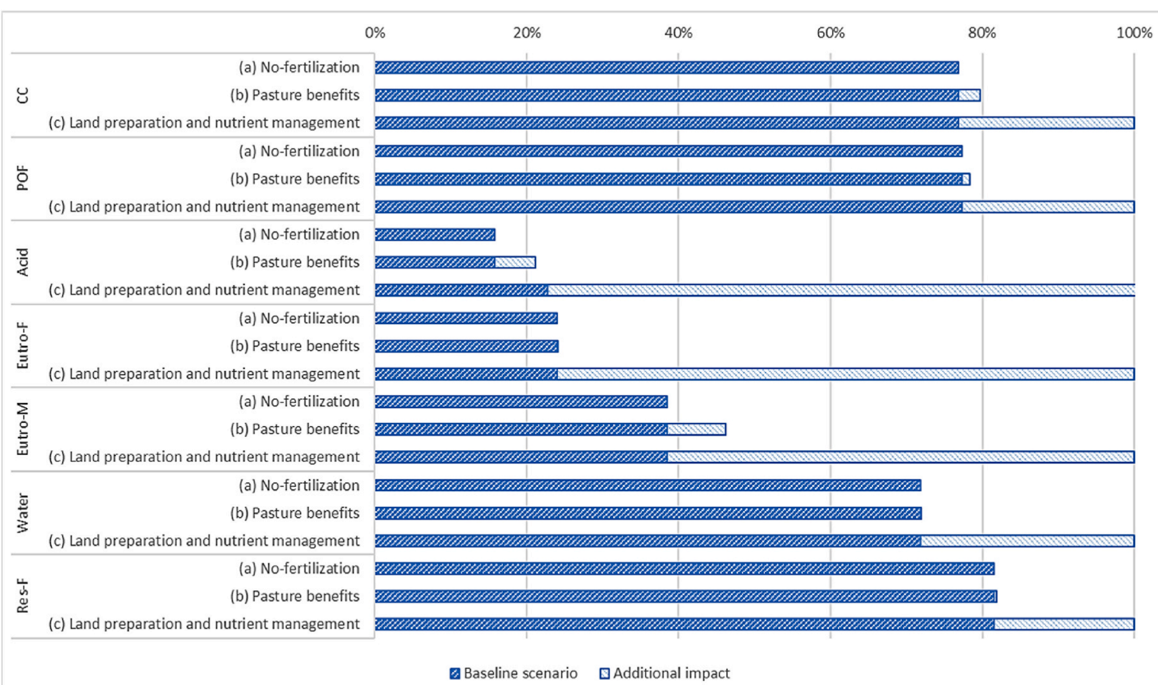

Fig. 7. Percentage increase in impacts for selected impact categories of (b) considering previous pasture as applying 25 t/ha of cattle manure during the first year of the orchard or (c) considering land preparation and nutrient management based on Keyes et al. (2015), compared to (a) the baseline scenario with no fertilization.

Alaphilippe et al., 2013; Keyes et al., 2015; Basset-Mens et al., 2016; Longo et al., 2017; Goossens et al., 2017; Asselin-Balençon et al., 2020) and fertilization (Milà i Canals et al., 2006; Alaphilippe et al., 2013; Alaphilippe et al., 2016; Vinyes et al., 2017; Longo et al., 2017; Iriarte et al., 2021). The literature highlights that the contribution of mechanical operations under organic production can be even larger to compensate for using fewer chemicals (Alaphilippe et al., 2013; Keyes et al., 2015; Goossens et al., 2017). In our study, the contribution of mechanical operations was even larger because no additional organic matter was applied to the soil due to its already high organic matter content. This was a specific characteristic of the orchard studied and should be revisited in the future. Nevertheless, as the farmer had

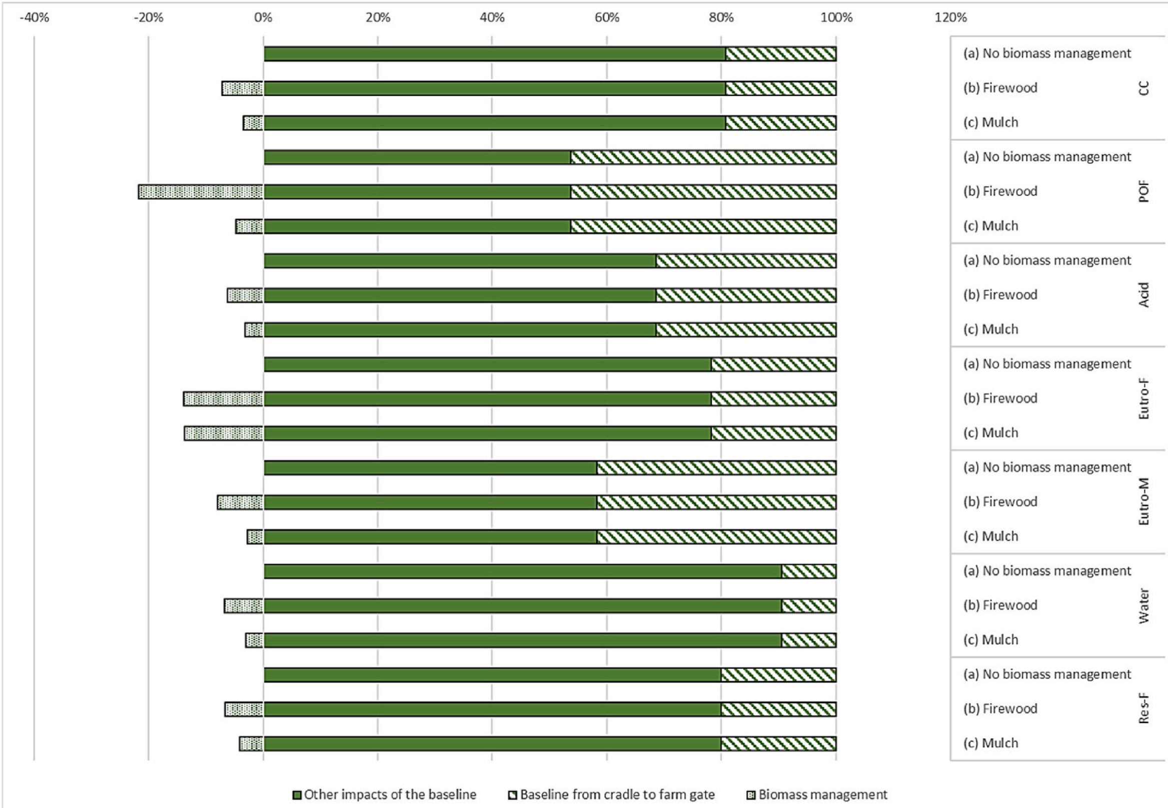

Fig. 8. Avoided impacts of considering the biomass used as (b) firewood or (c) mulch, compared to (a) the baseline scenario, which considered no benefit from the biomass (burnt on site).

received good yields for several years without fertilization, the farmer wanted to continue this practice.

4.1.2. *Other impact categories during the cultivation stage*

Because quantitative comparison of non-CC impact categories with other studies is more difficult, we compared our results to others qualitatively. Like for CC, mechanical operations were the main contributor to nearly every impact category. Only Eutro-F and Ecotox-F were influenced mainly by direct emissions (phosphate and sulphur, respectively). We examined the relative contribution of mechanical operations to non-CC impact categories to that in other studies. This comparison must be interpreted cautiously, as assumptions were necessary, because: (1) the systems were not always described in the same way, and mechanical operations were sometimes included in other sub-systems (e.g. spraying included in the pesticide sub-system), (2) impact categories were sometimes based on different characterization methods and (3) we sometimes had to estimate quantitative results from graphs. Overall, mechanical operations contributed greatly to impacts of apple cultivation, from the cradle to the farm gate, as in other studies of organic production (Fig. 11). This was expected, as we studied a non-conventional system with low inputs (especially fertilizers) and a higher contribution of mechanical operations. In other studies, the contribution of mechanical operations to certain impact categories was thus decreased by those of other activities (e.g. pesticide use, which influenced the toxicity of conventional production studied by Keyes et al. (2015); fertilization, which influenced eutrophication in most studies). In Mila i Canals. (2006), the contribution of mechanical work is, for example, minimized by the use of pesticides and fertilisers. This was confirmed by sensitivity scenarios in our study, in which the contribution of mechanical operations tended to decrease, which agreed with the literature.

4.1.3. *Other stages*

One main contributor to the system's total impacts was the processing and packaging stage, due to the use of glass bottles. To our knowledge, only two LCAs in the literature assessed apple juice and none assessed applesauce. However, comparing their results to ours did not seem relevant due to major differences in system boundaries, the production scale and type of packaging and processing. We thus found studies of other fruit juices or beverages, focusing on those that assessed the use of glass bottles as packaging. We excluded studies whose system boundaries differed greatly (e.g. excluding production of the beverage and its ingredients). Some existing reviews confirmed the large contribution of packaging (i.e. glass bottles) to total environmental impacts (Jourdaine et al., 2020). We also compared our results with those of studies that focused mostly on wine (Point et al., 2012; Neto et al., 2013; Bonamente et al., 2016; Penavayre et al., 2016; Rinaldi et al., 2016; Ferrara and De Feo, 2018), tomato-based products (Del Borghi et al., 2014) and carbonated beverages (Amienyo et al., 2013). Glass packaging contributed greatly to environmental impacts in literature studies, whose mean results were generally consistent with ours (Fig. 12). The most common impact category was CC, for which the contribution of glass packaging ranged from 14 to 74% (mean: 39%). In our study, glass packaging contributed more to environmental impacts (while remaining in consistent orders of magnitude) due to the relatively low environmental impacts of apple cultivation.

4.2. *LCA of alternative systems: a necessity facing difficulties*

As mentioned, LCAs of alternative systems are rare, even though these systems have existed for many years and tended to become more common as societal concerns have increased. El Hanandeh and Gharaibeh (El Hanandeh and Gharaibeh, 2016) used LCA to assess the environmental efficiency of olive oil micro-farms in Jordan. In this case,

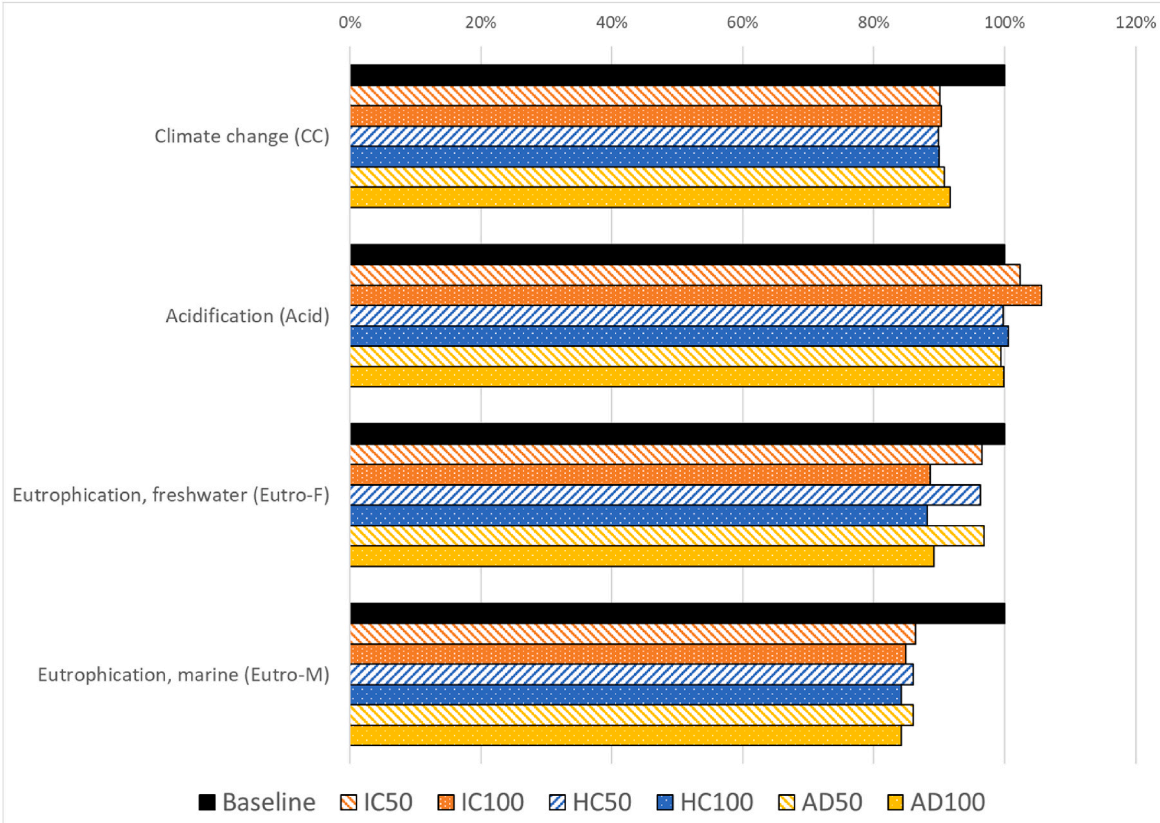

Fig. 9. Relative impacts of biowaste collection and treatment scenarios on total impacts of the entire value chain. IC: industrial composting, HC: home composting, AD: anaerobic digestion, 50: 50% collection efficiency, 100: 100% collection efficiency.

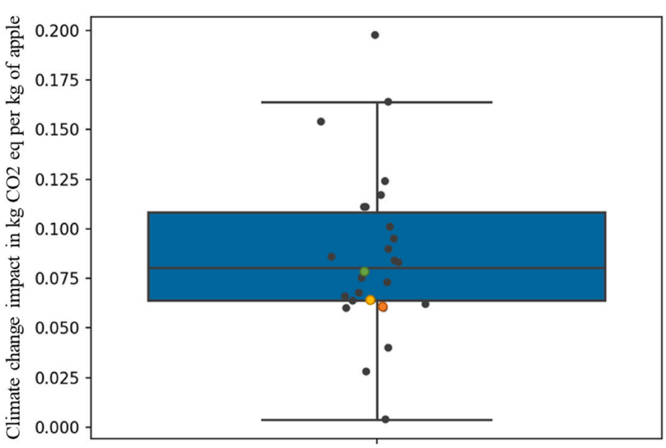

Fig. 10. Boxplot of potential climate change impact per kg of apple cultivation from the cradle to the farm gate in the literature (N = 23), including results for the baseline scenario of this study (orange) and the sensitivity scenarios (b) and (c) (yellow and green, respectively) *(mean = 0.087; median = 0.080; std = 0.041)*. Error bars represent 1.5 times the interquartile range. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

however, micro-farms are traditional farming models, not alternative models (El Hanandeh and Gharaibeh, 2016). In any case, the micro-farms were environmentally efficient due to practices that are common in alternative systems (e.g. little use of chemicals; little mechanization; alternative retail methods, such as bulk packaging). LCA was also applied to a small-scale low-input organic vegetable system in the UK (Markussen et al., 2014). This system can be considered alternative, as it combined high crop diversity and alternative distribution (i.e. box delivery). In addition, it was compared to high- and low-yielding organic production models, which cover some of the range described by Pépin et al. (2021). Kulak et al. (2015) applied LCA to farmer-bakers, whose farms are based on low-input wheat production, on-farm processing and direct distribution to consumers. LCA was also applied to community-supported agriculture, which can be considered here, despite there being many types of community-supported agriculture (Christensen et al., 2018; Zhen et al., 2020). Morgan et al. (2022) used LCA to assess impacts of a microbrewery, with a focus on packaging solutions (Morgan et al., 2022). Beyond the production stage, the issue of local food systems is strongly debated in the literature (Coley et al., 2009; Mundler and Rumpus, 2012). In any case, the lack of representativeness of alternative systems could lead to incorrect conclusions, especially when considering the difficulties in modelling organic systems in LCA (van der Werf et al., 2020). In the current context of developing environmental labelling of products and the objective to apply it to every product in the European Union, it seems necessary to provide the opportunity to everyone to use the methods and produce objective results for their systems.

Producing LCA for alternative systems faces a variety of issues that can be grouped into two challenges: the diversity of existing systems and the lack of appropriate LCIs. Technical decisions for alternative systems are often driven by the local context (through empirical knowledge), unlike those for conventional agriculture, which attempts more to drive the environment and apply the same system to different contexts. The diversity of alternative systems is also related to non-technical parameters. As described in the literature, alternative systems have objectives that go beyond agricultural production alone: preservation of natural resources, revitalization of a territory, access to good and healthy products, equity among individuals and human health concerns. These values come directly from each farmer's practices and are strongly

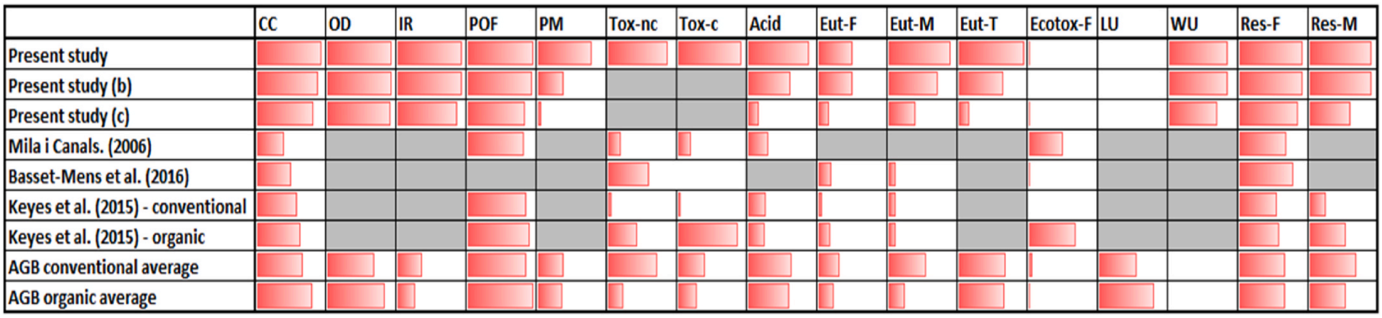

Fig. 11. Relative contribution of mechanical operations to apple cultivation from the cradle to the farm gate in the present study (with (b) considering previous pasture as applying 25 t/ha of cattle manure during the first year of the orchard or (c) considering land preparation and nutrient management based on Keyes et al. (2015)) and the literature. Cells are filled proportionally to the percentage of contribution. Grey cells indicate that no value could be derived from the literature. The length of bars does not reflect absolute impacts.

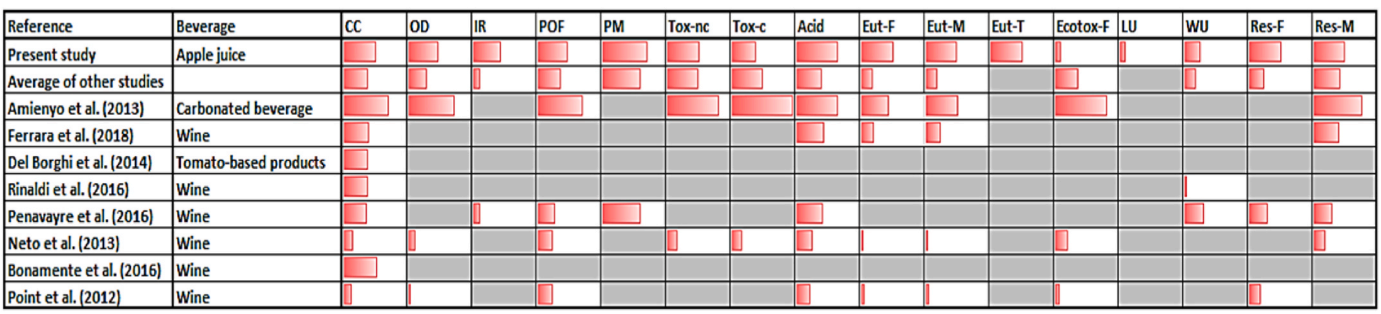

Fig. 12. Relative contribution of glass packaging to impacts of apple juice in the present study and beverages in the literature. Cells are filled proportionally to the percentage of contribution. Grey cells indicate that no value could be derived from the literature. System boundaries were not exactly the same for all studies, but those selected considered at least production of the beverage (and its ingredients) with glass packaging.

related to the farmer's life story, experiences, objectives and visions, as well as the geographical context. These factors induce high variability in environmental impacts, which makes it difficult to use means to describe and assess impacts of alternative systems. For example, a farmer may value providing quality products to the local population at a fair price, preserving biodiversity, exchanging with other people (e.g. collective farms) or helping people with disabilities. Farmers often try to address several of these values but also include the need to make their activity profitable and sustainable. To compare these alternative systems, it is important to extend the scope of the performances considered to include the other objectives pursued and potentially integrate them in a multi-criteria assessment. For example, the DEX method was applied to assess the overall sustainability of orchards (Alaphilippe et al., 2017) and other agricultural systems (Craheix et al., 2015; Estorgues et al., 2017; Rezaei et al., 2018; Le Féon et al., 2021). In the absence of representativity of alternative systems in LCA, there is a need to produce data and knowledge. There is also likely a need to produce many context-specific studies to (1) identify and recommend solutions to LCA shortcomings for these systems, (2) produce LCIs adapted to these systems to make future studies easier and (3) ultimately, recommend a range of LCA results that include some of the variability and tend to provide farmers with LCAs that are more representative of their systems than current databases. Tools already exist to help with this task, such as the LCI calculation platform MEANS (https://www6.inrae.fr/means), which requires some minor inputs (e.g. including more LCIs for alternative practices).

4.3. Next steps for this study

The results of this LCA identified four contributors to environmental impacts: apple cultivation, juice and applesauce packaging, distribution and consumption. Based on the literature, the apple cultivation studied already seems efficient, which leaves little room for improvement. The study, however, highlights the importance for farmers to manage biomass well when pruning and replacing trees. Concerning packaging, two options will be explored in the future with the farmer: an innovative packaging machine for small and mid-sized actors, and a zero-waste strategy for distribution. In the next step, the farmer will test the innovative machine to package at least the applesauce, which is currently packaged in glass jars. The farmer could benefit from its ability to switch among pouches of different size and thus produce different products for consumers. Different strategies will be tested for machines in terms of technology (e.g. using pouches of different material, such as conventional or bio-based plastic) and in terms of organization (e.g. a machine that remains stationary at the orchard or at a depot location, a machine with an operator that moves among farms). In parallel, reusable glass bottles will be tested for the juice, as the farmer recently thought about using them. However, the use of alternative materials for packaging could induce possible effects on the nutritional and organoleptic qualities of the product, as well as environmental impacts that are not widely assessed by LCA (e.g. microplastic pollution). This should be included in further studies.

Different retail scenarios will be also tested. For example, the farmer recently opened a store at the orchard, which was not considered in the LCA due to insufficient long-term data. Environmental impacts of these strategies will be assessed with LCA to provide eco-design recommendations to technology developers and help choose among several organizational opportunities. As the study demonstrates the large contribution of consumer transport of products, this transport will be carefully studied in future scenarios. While the farmer has little ability to manage consumer waste, the sensitivity analysis showed that upcoming regulations on separate biowaste collection in France should influence the environment positively as long as the collection is efficient. As a link in the chain, farmers could help promote use of biowaste in direct relation with consumers. These results should be investigated further, however, as they were based on multiple assumptions that were independent of the geographical context. Indeed, the geographical context influences the amount of biowaste, the existing treatment facilities, and the local potential to use by-products (e.g. compost, biogas and digestate from AD).

To go beyond environmental impacts, it is planned to assess overall sustainability by including societal and economic issues along with environmental impacts. The LCA results provided by this study will be used as a baseline scenario and supplemented with societal and economic indicators. The sustainability of current and future situations will be assessed and compared using multi-criteria methods. This will provide the farmer with broader results and guidance about the orchard. It can also be a way to better consider societal values in such systems that are difficult to consider in the scope of LCA. Ultimately, the necessary complementarity of methods will be investigated. Providing social LCA results could also a track to investigate in the future, in order to grasp the benefits associated with some of the peculiarities of non-conventional agricultural systems.

5. Conclusion

This study provides an overview of environmental impacts of an entire apple value chain, including processing into juice and applesauce. It constitutes a representative baseline scenario that allows recommendations about future developments to be made to the farmer. Building this scenario faced the lack of LCIs and representativeness in databases and the lack of existing literature. The study helps respond to the lack of representativeness of alternative systems in LCA by studying the environmental impacts of an alternative apple value chain, including juice and applesauce. It generated a specific LCI, LCIA results of the entire value chain (confirming the utility of examining packaging for such systems), comparison to the literature and discussion about the need to assess alternative systems.

In terms of data, a full LCI of a specific alternative system was produced. It concerns the entire value chain: cultivation, the production of three products, and their retail and consumption. Waste management, as well as transport, were modelled and discussed. In addition, it was necessary to approximate LCIs for inputs that were specific to organic production and not in databases. This was done in part by adapting the approach of Montemayor et al. (2022). We do not claim that the LCI represents a certain type of system, as it is based on a specific value chain, and the variability among alternative systems is high. Given this variability, additional studies should be performed to produce LCIs for alternative systems. The potential to group some of them in a typology could then be discussed.

In terms of results, the cultivation phase of our case study was more efficient than those in the literature. This is not surprising, as no fertilization was used in the baseline scenario because the orchard benefitted from the previous pasture. This important issue of fertilization was highlighted, as even in the most fertilized scenario of the sensitivity analysis, the CC impact of the system lay below the mean of that in the literature. As no fertilization was used, the main contribution of the cultivation stage came from mechanical operations. This is consistent with other studies, especially for organic production. In addition, a sensitivity analysis was used to analyse the influence of biomass management at the orchard's end-of-life. The results also showed a large contribution of juice and applesauce to total impacts, mainly due to the use of glass packaging. Again, this is consistent with the literature. Most importantly, it confirms the utility of working on packaging in the rest of the project. As the orchard's apple cultivation already has low impact, there is probably more room for manoeuvre in the rest of the value chain, especially on packaging solutions. Technical options (new machine and packaging) and organizational options (reusable bottles) will be studied in the rest of the project. The results also show a large contribution at the end of the value chain, due to consumers' trips for purchase and to the management of apple waste. The latter illustrates a major issue in waste management that should change soon in France due to the expansion of separate collection of biowaste. The sensitivity analysis showed that this should help decrease most environmental impacts if biowaste is collected efficiently.

With the growing interest to inform consumers about environmental impacts and the related upcoming European Union regulation on the environmental footprint, it is crucial to provide access to fair environmental assessment to every producer and ensure that assessments are validated by experts. Some alternative systems appear to be underrepresented in the literature and databases. Thus, producing LCI, LCIA and guidance to apply the methods to represent the high variability should be an objective for further research. It is also important to consider how to include externalities in the evaluation as societal values that are common in such systems, but also environmental benefits that are not considered by LCA. Coupling methods and developing a multi-criteria approach to assess sustainability should be encouraged.

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Author contributions

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared the link to my data

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Appendix A. Supplementary data

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