*agriculture*

*Article*

# Life Cycle Assessment of Dried Organic Apple Value Chains Considering Conventional and Heat-Pump-Assisted Drying Processes: The Case of Sweden

**Techane Bosona**

Department of Energy and Technology, Swedish University of Agricultural Sciences, P.O. Box 75651 Uppsala, Sweden; techane.bosona@slu.se

**Abstract:** The increasing population pressure and demand for quality food, and the significant burden of agriculture on the environment, impede the sustainable development of the food sector. Understanding the environmental performance of different agricultural technologies and food value chains and identifying improvement opportunities play important roles in the sustainable development of this sector. This article presents the results of an environmental impact assessment of organic dried apples produced and supplied in Sweden, which was conducted using primary and literature-based data. A "cradle-to-consumer gate" life cycle analysis (LCA) method with a functional unit (FU) of 1 ton of fresh organic apples at the farm stage was used while considering conventional drying and heat-pump (HP)-assisted apple-drying techniques. The main environmental impact categories investigated were cumulative energy demand (CED), climate change impact (GWP), acidification potential (AP), and eutrophication potential (EP). The results indicate that the total CED values were 7.29 GJ and 5.12 GJ per FU for the conventional drying and HP-assisted drying methods, respectively, i.e., a reduction of about 30%. Similarly, the GWP values were 130 kg $CO_2$ eq and 120 kg $CO_2$ eq per FU, respectively. These findings highlight the importance of improving energy use and process efficiency to increase the sustainability of dried organic apple value chains.

**Keywords:** organic apple; apple drying; environmental impact; life cycle assessment; Sweden



**Citation:** Bosona, T. Life Cycle Assessment of Dried Organic Apple Value Chains Considering Conventional and Heat-Pump-Assisted Drying Processes: The Case of Sweden. *Agriculture* **2024**, *14*, 461. https://doi.org/10.3390/agriculture14030461

Academic Editor: Changyou Li

Received: 17 January 2024
Revised: 20 February 2024
Accepted: 29 February 2024
Published: 12 March 2024



## 1. Introduction

### 1.1. General Introduction

Agriculture covers about 40% of the global land area and contributes to 70% of global water withdrawal and 30% of greenhouse gas emissions [1]. The demand for new agricultural land is expected to increase due to the effects of population pressure, diet change, and biofuel production [2]. Other challenges are food loss and waste (FLW) issues, which exacerbate the environmental impacts of the food sector [3]. Reducing FLW, e.g., in the food processing and food service sectors, can significantly reduce greenhouse gas (GHG) emissions and energy use [4] and improve resource use efficiency [3]. Reducing FLW should occur at all stages of the supply chain, e.g., by improving food processing and increasing shelf life. Both agricultural and post-harvest processing should be improved to reduce environmental impacts. This study focuses on organic apple-drying processes that lead to a reduction in FLW while increasing the shelf life of organic apples.

Organic food production and societal interest in organic food are growing [5]. However, the low yield of organic food production is one of the factors that could reduce the competitiveness of organic food products regarding environmental sustainability. For instance, it promotes the efficient use of energy and improves soil and water quality and biodiversity [6]. Organic food is also associated with consumers' health, animal welfare, biodiversity, and environmental benefits [5]. Considering the importance of organic food production methods, the European Commission has provided general guidance for organic food production (Regulation (EC) 834/2007), which includes the defined general rules for the processing of organic food. In Sweden, quality requirements for organic farming are mainly issued by KRAV, which is an incorporated association including farmers, processors, consumers, and firms with environmental and animal welfare interests [7]. KRAV has issued regulations regarding mechanical weed-controlling methods and the avoidance of chemical pesticides.

Table 1 presents Sweden's apple production (including conventional production) in comparison with other EU countries. Sweden produces only about 0.2% of the total apple production of the EU (12.7 million tons), while Poland, Italy, and Germany produce about 25%, 19.2%, and 7.7%, respectively (see Table 1). Although there is an increased demand for organic apples in Sweden, the production levels in Sweden do not satisfy the demand [7]. Therefore, about 85% of apples for consumption are imported from other countries.

**Table 1.** Production of apples in some EU member states [8].

| Country | Yearly Apple Production | |
|---|---|---|
| | **Harvested Production (in 1000 Tons)** | **Share of EU Production (%)** |
| EU | 12,685.4 | 100% |
| Poland | 3168.8 | 25 |
| Germany | 973.5 | 7.7 |
| Italy | 2441.6 | 19.2 |
| Spain | 593.6 | 4.7 |
| Romania | 459.6 | 3.6 |
| Sweden | 25.4 | 0.2 |

### *1.2. Literature Review on LCA of Apple Fruits*

The life cycle assessment (LCA) approach can assist in identifying more sustainable food production and supply options [9]. Some studies (see Table 2) were conducted to understand the environmental performance of conventional and organic apple supply chains [10,11]. Depending on the system boundaries, agricultural location and operation, and the nature of fruit supply chains, the environmental impact values can vary (see Table 2). A study by Zhang et al. [10] indicated that integrated soil–crop–market management could increase the benefits of apple value chains from environmental and financial perspectives. The use of organic fertilizers and reduced pesticides in apple cultivation can reduce some of the negative impacts on the environment and improve soil and food quality [12].

At the agricultural production stage of apple fruit, diesel fuel, fertilizers, and pesticides can contribute more to negative environmental impacts [13]. In some cases, irrigation and field operations greatly contribute to environmental impacts [14]. In long supply chains of apple fruit, transportation contributes to a significant portion of the carbon footprint. For instance, Iriarte et al. [15] indicated that ocean freight contributed to 39.2% of the carbon footprint of apple supply from Chile to the UK when considering the entire supply chain. Longo et al. [16] indicated that the packaging stage contributes to a significant portion of the energy impact at the post-harvest stage. Vinyes et al. [17] conducted a cradle-to-grave LCA study of apple fruit and reported a carbon footprint of 0.302 kg $CO_2$ eq per kg of fresh apple, of which about 39%, 36%, and 23% were the contributions of the retailer, agricultural production, and consumption stages (see Table 2). An LCA study conducted in Turkey by Ekinci et al. [18] indicated that organic apple production performs better than conventional systems in terms of both energy demand and carbon footprint.

FLW is one of the challenges in the fruit sector [19]. Jeswani et al. [20] reported that at the primary production, distribution, and consumption stages of the fresh apple value chain, losses were 20%, 9.6%, and 17.7%, respectively. Similarly, Loiseau et al. [21] revealed that apple losses at primary production (e.g., during sorting and calibration), storage, packaging, and retail storage were about 20%, 2%, 4%, and 5%, respectively.

Svanes et al. [22] indicated that apple loss along the supply chain was about 12%. Therefore, reducing FLW along the entire fruit supply chain is one of the pathways to sustainable food systems [3,20]. Reducing FLW can not only increase access to food but also reduce the environmental impacts and nutritional losses associated with FLW. For this, efficient post-harvest processing is needed. Energy consumption during the drying process can significantly contribute to environmental impacts such as carbon footprints [23,24]. In the fruit and vegetable sector, product refrigeration is one of the activities that has a high environmental impact [25]. In particular, overproduction increases the challenges of preservation. In this regard, the drying process reduces the need for refrigeration.

HP drying of apples is an effective technology that can lead to less environmental burden through efficient energy use during the drying process [23]. However, there is a lack of LCA studies on apple drying, and more studies are required to explore the most environmentally friendly methods of drying apples. This research gap needs to be addressed, as there is increasing interest among consumers in knowing more about the impacts of the fruit they consume [26]. In this regard, the current study contributes to increasing the data and knowledge base on the environmental performance of processed fruits.

**Table 2.** Some LCA studies of apple value chain.

| Scope | Functional Unit | Country | Yield (t/ha) | CED (GJ/FU | GWP (kg $CO_2$ eq/FU) | Ref. |
|---|---|---|---|---|---|---|
| Cradle-to-farm gate; conventional apple production | Ton of fresh apples | Greece | 32.4 | 1.21 | 89 | [14] |
| Cradle-to-consumer gate | Kg of exported fresh apples | Chile (production); UK (consumption) | 47.2 | na | 0.54 | [15] |
| Cradle-to-consumer gate | Fresh apples | France | 37.8 | | | [21] |
| Cradle-to-consumer gate; conventional | Ton of fresh apples | Italy | 70 | 11.4 | 612 | [16] |
| Cradle-to-consumer gate; organic | Ton of fresh apples | Italy | 50 | 11.2 | 588 | [16] |
| Cradle-to-grave | Kg of fresh apples | Spain | 48.81 | na | 0.302 | [17] |
| Conventional production | Ha of apple orchard | Turkey | 40.9 | 29.2 | 1464.07 | [18] |
| Organic production | Ha of apple orchard | Turkey | 38.7 | 25.94 | 1344.27 | [18] |
| Cradle-to-farm gate | Kg of fresh apples | Italy | 58.6 | na | 0.514 | [25] |
| Cradle-to-farm gate | Ton of fresh apples | Portugal | na | na | 76 | [23] |
| Cradle-to-farm gate (conventional production system) | Ton of fresh apples at farm gate | Belgium | 43.1 | na | 67.7 | [11] |
| Cradle-to-farm gate (integrated production system) | | | 53.5 | na | 65.9 | |
| Cradle-to-farm gate (organic production) | | | 48.6 | na | 154 | |
| Cradle-to-grave | Kg of fresh apples | UK | | 0.019 | 1.4 | [24] |

The environmental impacts of food production vary from country to country and even from region to region [11]. Therefore, more scientific data and more LCA studies focusing on different geographical areas are required. The increasing consumption, and hence production, of fruit could lead to a greater impact on the environment [27]. However, few data are available to evaluate the environmental impacts and mitigation potential and economic benefits of fruit value chains in Sweden. Specifically, there are limited studies on dried organic apple value chains, and to the author's knowledge, there is no LCA study of dried apple value chains in Sweden. This study aims to address this gap. In addition, product environmental footprint is becoming an important indicator of sustainability. Therefore, quantifying the impact per product is important. An environmental impact assessment that considers the entire value chain of fruits would allow researchers to provide more comprehensive information to the public and policy makers. In addition to attempts to make primary fruit production more sustainable, it is important to make the post-harvest process and the rest of the value chain more resource-efficient with a lower environmental footprint [17,21,25].

The objective of this study was to conduct an environmental impact assessment of dried organic apple value chains by using the LCA approach while considering conventional and HP-assisted drying techniques. More detailed objectives and the scope of this study are provided in the next section. The rest of this article is organized as follows: Section 2 describes the materials and methods used; Section 3 presents the main results; Section 4 discusses the results; and Section 5 provides the conclusions.

## 2. Materials and Methods

Organic apples produced and supplied in Sweden were used in this study. A "cradle-to-consumer gate" LCA was conducted by using the LCA approach. The standardized procedures of LCA (ISO 14040:2006 [28] and ISO 14044:2006 [29]) were followed during modeling. In this study, two options for apple drying, one with a conventional dryer and the other with an HP-assisted dryer, were modeled with SimaPro LCA software, v8.5.2. Energy demand (primary energy consumption) analysis was conducted by using Cumulative Energy Demand, CED V1.10 [30,31]. For the assessment of different environmental impact categories, ReCiPe 2016 Midpoint (H) V1.02 was used.

### *2.1. Goal and Scope Definition*

The objective of this LCA study was to investigate the influence of drying processes on the environmental impacts of organic apple value chains. Conventional drying and HP-assisted drying methods were applied. The following stages were included: agricultural production, drying process, and post-harvest handling at the processing facility and retailer, and transport. The system boundary excluded the consumption level and waste management. A functional unit (FU) of 1 t (metric ton) of fresh apples at the farm stage, excluding the packaging weight, was considered. Since many LCA studies of apple have been reported for fresh products, the current FU enables easy interpretation of the results and comparison of the impacts of dried apple with those of fresh apple value chains, taking into consideration the effect of the system boundary of each study. Using an appropriate FU is essential in LCA studies, especially when assessing the environmental impacts of food value chains [16,32].

### *2.2. System Boundary and Product Value Chain Description*

In this LCA study, major processes from the farm stage to delivery to consumer gate were included (see Figure 1). The organic apple product was considered to be locally produced and supplied in Sweden. In the current LCA study, the dried organic apple value chain was investigated by focusing on different drying techniques. Figure 1 presents a simplified flowchart of the system boundary.

#### 2.2.1. Agricultural Production of Organic Apples

Once established, an apple plant can produce fruit for many years. On average, the apple plant has a productive life span of 15 years, and the full production starts in the 5th year. Organic apple farms produce lower yield than conventional farms [16]. Based on primary data acquired from 4 organic apple orchards in Sweden, the average annual yield of 12.5 t/ha was used in this LCA study. Studies indicate that the annual yield of apples varies between 10 t/ha and 40 t/ha [7,33,34].

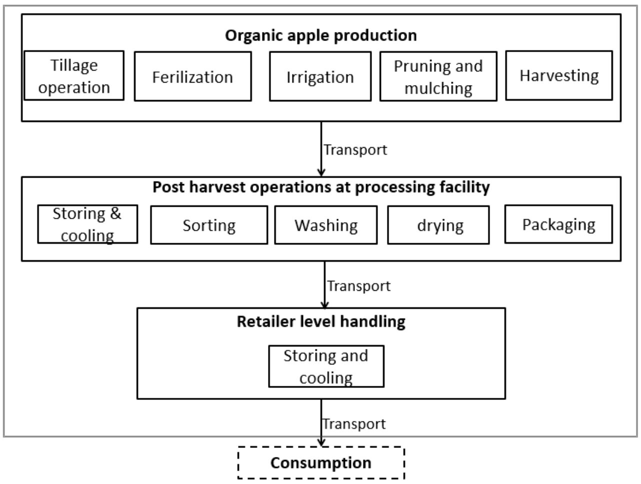


**Figure 1.** Simplified flowchart illustrating different stages of the value chain.

Fertilizer and irrigation water supply and harvesting activities at the farm stage in terms of farm operations such as ploughing and planting of apple trees were included. Energy sources considered for such operations include diesel and electric energy sources. Pruning activities include the crushing/mulching of pruned leaves and branches. Manual harvesting activity was considered but was assisted by two tractors and a light vehicle for farm activities. The diesel quantities estimated for tillage, pruning, and harvesting operations were 0.21 kg, 3.34 kg, and 9.83 kg, respectively, per FU.

### 2.2.2. Apple Drying and Post-Harvest Handling

The main activities at the post-harvest stage include apple drying (see Figure 2), packaging, storage, and retailing. In order to improve the product quality, apple sorting and washing processes were considered. For this, about 5.33 MJ of electric energy and 2.9 t of water per FU were estimated and included in data inventory. For storage cooling, 34.4 MJ per FU was considered where only 20 days of storage duration was considered, although fresh apple fruits can be stored for up to 12 months [34].

**Figure 2.** Example of dried apple products [35].

A conventional dryer and a HP-assisted dryer were considered in this case. The conventional dryer has a life span of 20 years and 600 kg mass. Its model was HT8, sourced from Innotech in Germany. For the HP-assisted dryer, a 500 kg HP with R744 model was considered. In order to understand the influence of the HP-assisted technique on environmental impact, the dried apple from the conventional dryer and that from the HP-assisted dryer were analyzed separately (see Figure 3).

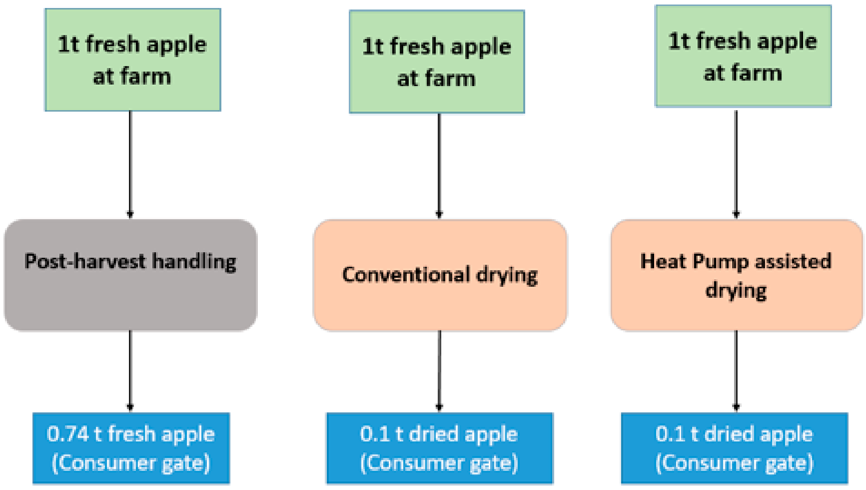


**Figure 3.** Simplified illustration of apple-drying options.

The energy consumption for dehydrating the fresh apple was estimated based on 1.2 kg water per 1 kwh and 2.2 kg water per 1 kwh for the conventional dryer and HP-assisted dryer, respectively. The moisture content (MC) of fresh apple is about 82%, which can be reduced to about 11% by the drying process. The MC of dried apple is 8–12%. From 100 kg of fresh apple input to the dryer, up to 12 kg of dried apple can be obtained. In the current study, about 110 kg dried apple per FU was considered, after allowing for losses along the value chain from the farm to the drying process. Packaging materials and processing were considered in this study. Packaging plastic (polyethylene) and cardboard were used. About 0.3 kg plastic and 12 kg cardboard per FU were used. The energy requirement for apple cooling in retail was quantified based on the study by Stadig [34] and considering 20 days' duration at the retailer. Accordingly, 34.4 MJ and 5 MJ of electric energy were considered per FU of fresh apple and dried apple, respectively.

### 2.2.3. Transport Segments

The transport stage includes three segments of transporting the product (see Figure 4): transport of fresh apples from the farm to the processing facility where apple drying is assumed to be carried out (80 km); transport of dried apples from the processing facility to the retailer (50 km); and transport of dried apples from the retailer to the consumer's gate (5 km). The indicated value in each transport segment is for a single trip's distance. Except for the last segment, a truck with a 7.5–16 ton capacity was considered with its background data in the ecoinvent database, while a passenger car was considered for the last segment.

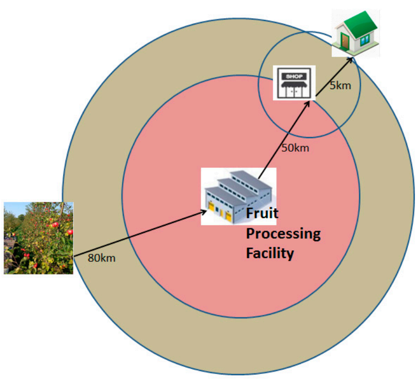


**Figure 4.** Conceptual illustration of typical transport configuration for collection (from farms) and distribution of locally produced organic apples.

### 2.3. Life Cycle Inventory

Considering the main life cycle stages, namely, agricultural production, post-harvest handling and processing, and transport (see Table 3) and consulting both primary and literature-based data sources, a life cycle inventory (LCI) was conducted. At the agricultural production stage, the average values were estimated considering the entire life span of the apple plant, which is about 15 years. Data regarding the drying process using the conventional method and the HP-assisted drying method were included at the post-harvest handling and processing stage. The data were quantified per FU of this LCA study, which is 1 ton of fresh apples at the farm stage, i.e., the amount to be dried and supplied to consumers as dried organic apple. The data regarding the conventional dryer and heat pump were estimated based on a life span of 20 years and working time of 25 days per month. Electricity production in Sweden with medium voltage was assumed and applied from the ecoinvent database. As part of improving data quality, priority was given to primary and secondary data related to product location or region. Regional (Europe) or global data were considered only when there was a lack of localized data.

**Table 3.** LCI data at different stages of organic apple value chains per FU.

| Description | Unit | Quantity | Data Source * |
|---|---|---|---|
| Agricultural production | | | |
| Diesel for ploughing, harrowing, and planting | kg | 0.21 | [34] |
| Organic fertilizer | kg | 12 | [16] |
| Fertilizer transport distance | km | 50 | |
| Water for irrigation | kg | 54,000 | Estimated based on the literature [34] |
| Electricity for irrigation | MJ | 64.42 | |
| Energy for pruning (including crushing/mulching) | kg | 3.34 | |
| Energy (diesel) for harvesting activities | kg | 9.83 | |
| Post-harvest process | | | |
| Energy for storing (cooling) | MJ | 34.4 | Estimated considering 20 days before drying process |
| Water (washing etc.) | kg | 2900 | [16] |
| Energy for sorting | MJ | 5.33 | [34] |
| Electricity for apple slicing | kwh | 1.3 | Estimated considering a commercial machine of 1.5 t/2 kwh capacity |
| Apple drying | | | |
| Fresh apple at farm (FU) | t | 1 | |
| Fresh apple at drying processing facility | t | 0.74 | Reducing 26% cumulative loss [36] |
| Dried apple | t | 0.1 | It is 12% of the fresh apple weight just before drying process [35] |
| Conventional dryer | | | |
| Dryer weight (stainless steel) | kg/FU | 0.37 | Estimated based on dryer mass of 600 kg and life span of 20 years [35] |
| Electricity for drying 0.74 t (i.e., per FU) | kwh | 543 | Estimated based on data from [35] |
| Heat pump (HP) drying | | | |
| Dryer weight (stainless steel) | kg/FU | 0.37 | Estimated based on dryer mass of 600 kg and life span of 20 years [35] |

**Table 3.** *Cont.*

| Description | Unit | Quantity | Data Source * |
|---|---|---|---|
| Weight of HP dryer (steel) | kg/FU | 0.31 | Based on HP weight of 500 kg and life span of 20 years; it is a customized HP (i.e., heat pump + same conventional drier) [35] |
| Electric energy for drying 0.74 t fresh apple (i.e., per FU) | kwh | 296 | Estimated based on 2.2 kg water/kwh (and 12 kg dried apple per 100 kg fresh apple) |
| Energy for dried apple packaging process | MJ | 0.72 | Estimated based on the literature [34] |
| Dried apple weight (per FU) | ton | 0.1 | Estimated based on data from [35] |
| Packaging plastic for dried apple (polyethylene) | kg | 0.3 | |
| Packaging carton for dried apple | kg | 12 | Estimated based on the literature [16] |
| Retailer | | | |
| Electricity for cooling at retailer for fresh apple | MJ | 17.2 | Estimated based on the literature [34] |
| Transport | | | |
| Transport from farm to processing facility | km | 80 | Assumed based on information from primary data survey |
| Transport from processing facility to retailer | km | 50 | [37] |
| Transport from retailer to consumer | km | 5 | Assumption |

* Values are recalculated and provided per functional unit based on information in the indicated references.

## 2.4. Life Cycle Impact Assessment

### 2.4.1. Impact Categories

The main environmental impact categories considered in this study were cumulative energy demand (CED), global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP), with more focus on CED and GWP. Energy demand is an input-related indicator, while GWP, AP, and EP are output-related indicators [32,38].

### 2.4.2. Allocation Principle

Allocation problems in the current study are related to the by-products and wastes of fresh apples. The losses along the supply chain (i.e., up to the drying process) were considered. Only the quantity left after reducing the losses at the upstream stages of the supply chain was considered in the drying process. This enables one to avoid unnecessary extra environmental burden results. However, the environmental burden from the agricultural production of the lost product was allocated to the quantity dried and consumed (i.e., assigned to a FU of 1 ton of fresh product at the farm stage) because, in this study, no alternative use of lost food was considered. In some cases, part of the food waste can be used for animal feed or other purposes. In such cases of vegetables and fruits, allocation problems can be considered [39]. In the case of purchasing food, there could also be an allocation problem because, usually, different food types can be purchased together. The specific food under consideration (i.e., apple) can constitute only a portion of the total purchase, and environmental burden was assigned accordingly by using mass allocation.

### 2.4.3. Sensitivity Analysis

In the organic apple-drying process, the energy consumption of the drying process was based on data from experimental activities. At the commercial scale, it can vary. Therefore, sensitivity analyses were conducted by varying drying energy by (−/+) 30% and assuming that other data remained the same, i.e., by reducing or increasing the energy consumption of the basic scenarios. In the basic scenario of this study, the energy consumption values for apple drying were 543 kwh (conventional dryer) and 290 kwh (HP-assisted dryer) per FU. This sensitivity analysis enables one to gain insight into how improving the efficiency of energy use and the two drying methods could influence the environmental impacts of dried organic apple value chains.

## 3. Results

### *3.1. Cumulative Energy Demand of Apple Value Chain*

The CED values at the agricultural stage and transport stage were the same for the conventional and HP-assisted drying options. The CED value at the agricultural stage was estimated to be 1.33 GJ, while it was about 0.84 GJ at the transport stage (see Figure 5). At the post-harvest stage, there was a reduction from 5.11 GJ (conventional dryer) to 2.95 GJ (HP-assisted dryer), i.e., a reduction of about 42%. The total CED values were 7.29 GJ and 5.12 GJ for the conventional drying and HP-assisted drying methods, respectively, i.e., a reduction of about 30%. This indicates that introducing HP-assisted drying techniques has great potential for improving the fruit-drying process. Figure 5 also indicates that the post-harvest stage is a hot-spot for energy consumption, followed by the agricultural stage. Therefore, efforts at further improvement should focus on these stages. Unlike in the supply and consumption of fresh apples, the dried apple value chain consumes more energy at the processing stage. On the other hand, the drying process reduces the volume and weight of apples and their packaging, reducing the fuel required for transport.

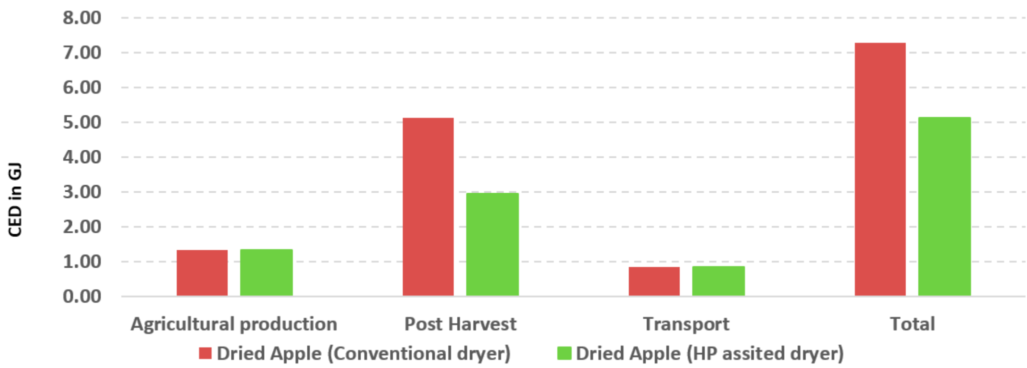


**Figure 5.** Energy consumption at different stages of organic apple value chain. Values are given in gigajoules (GJ) per FU.

For apple drying, the electric energy mix of Sweden was used. Figure 6 indicates that, due to the electric energy consumption of the drying process, the share of non-renewable energy sources such as fossil and nuclear energy is high. In the case of conventional drying, the share of nuclear and fossil energy were 45% and 32%, respectively, while the values were 37% and 44% in the case of HP-assisted drying. This highlights the fact that the use of renewable energy sources should be increased where possible to reduce the non-renewable energy use and improve the sustainability of dried organic apple value chains.

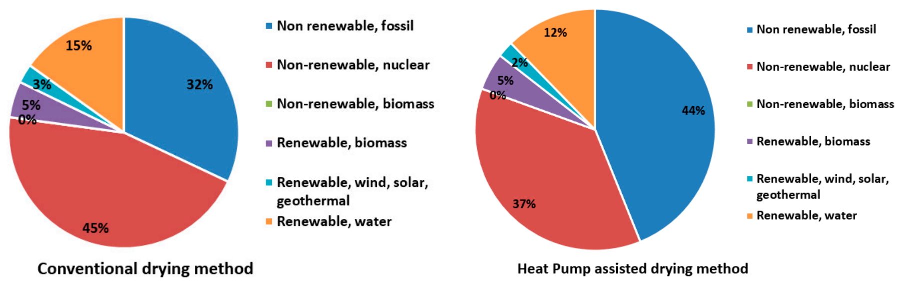


**Figure 6.** Contribution of different energy sources to total CED in dried apple value chains considering conventional and HP assisted drying methods.

### 3.2. Global Warming Potential of Organic Apple Value Chain

The total GWP values were estimated to be 130 kg $CO_2$ eq and 120 kg $CO_2$ eq per FU for the conventional and HP-assisted drying methods, respectively. Figure 7 shows that GWP values at the agricultural production, post-harvest, and transport stages were found to be 35 kg $CO_2$ eq, 39 kg $CO_2$ eq, and 57 kg $CO_2$ eq per FU, respectively, for the conventional drying method. Similarly, for the HP-assisted drying method, the values were found to be 35 kg $CO_2$ eq, 29 kg $CO_2$ eq, and 57 kg $CO_2$ eq per FU, respectively, for the life cycle stages mentioned above. In both drying options, the transport stage contributed more emissions due to the fossil-based fuel considered for transport activities. Due to the improvement in energy consumption for apple drying, the emission value was reduced at the post-harvest stage for the HP-assisted drying option, i.e., emissions related to energy production and supply decreased as energy consumption was reduced (see Figures 7 and 8). As shown in Figure 8, the contribution of the agricultural production, post-harvest, and transport stages to the total GWP were 27%, 30%, and 43%, respectively, for the conventional drying option. Similarly, for the HP-assisted drying option, the values were 29%, 24%, and 47%, respectively, for the indicated life cycle stages.

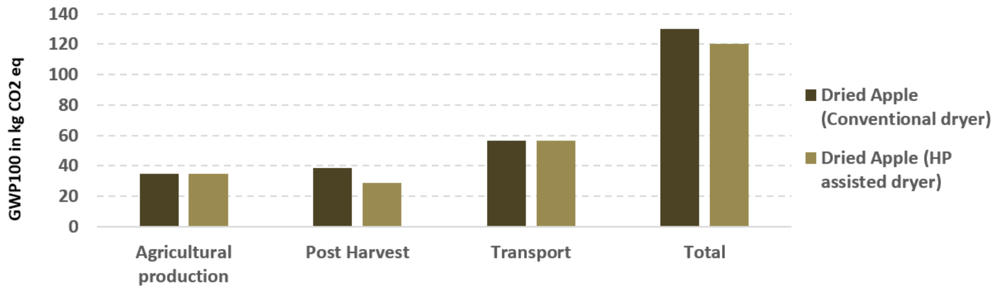


**Figure 7.** Climate change impact of different stages of dried organic apple value chain in kg $CO_2$ eq per FU.

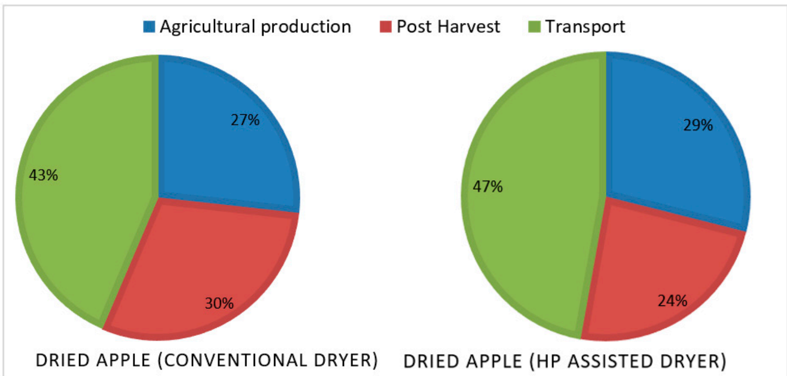


**Figure 8.** Contribution of different life cycle stages to total GWP: comparison of conventional dryer (as % of 130 kg $CO_2$ eq) and HP-assisted dryer (as % of 120 kg $CO_2$ eq).

### 3.3. Acidification and Eutrophication Impact of Organic Apple Value Chain

Table 4 presents the quantified acidification and eutrophication impact values. Terrestrial acidification is higher in the agricultural production stage, while eutrophication is higher in the post-harvest stage. The total quantified values per FU for terrestrial acidification, freshwater eutrophication, and marine eutrophication were 0.3781 kg $SO_2$ eq, 0.0368 kg P eq, and 0.0079 kg N eq, respectively, for the dried apple when using the conventional drying method. For the HP-assisted drying method, these values were 0.3482 kg $SO_2$ eq, 0.0318 kg P eq, and 0.0063 kg N eq, respectively. Irrigation activities were the major sources of acidification and eutrophication impacts at the agricultural production stage. The results indicated that the improvement in the drying process due to the HP-assisted drying method could reduce the acidification and eutrophication impacts. For instance, the terrestrial acidification and freshwater eutrophication at the post-harvest stage were reduced by about 26% and 28% respectively, in the HP-assisted drying method when compared with the conventional drying method. At both the post-harvest and transport stages, the energy required for apple drying, production, and supply of packaging material mainly contributed to the acidification and eutrophication impacts. The results indicate that improvement at the agricultural production stage, such as an irrigation system and efficient energy use at post-harvest handling and processing, could lead to a sustainable organic apple production and supply system.

**Table 4.** Acidification and eutrophication impacts of dried organic apple value chain. The values are provided per FU.

| Impact Category | Unit | Agricultural Production | Post-Harvest | Transport | Total |
|---|---|---|---|---|---|
| Dried apple (conventional drying) | | | | | |
| Terrestrial acidification | kg $SO_2$ eq | 0.1511 | 0.1169 | 0.1101 | 0.3781 |
| Freshwater eutrophication | kg P eq | 0.0126 | 0.0181 | 0.0061 | 0.0368 |
| Marine eutrophication | kg N eq | 0.0010 | 0.0064 | 0.0005 | 0.0079 |
| Dried apple (HP-assisted drying) | | | | | |
| Terrestrial acidification | kg $SO_2$ eq | 0.1511 | 0.0870 | 0.1101 | 0.3482 |
| Freshwater eutrophication | kg P eq | 0.0126 | 0.0130 | 0.0061 | 0.0318 |
| Marine eutrophication | kg N eq | 0.0010 | 0.0048 | 0.0005 | 0.0063 |

### *3.4. Sensitivity Analysis*

Table 5 presents the results of the sensitivity analysis. A drying energy of 543 kwh (conventional drying) and 290 kwh (HP-assisted dryer) per FU was used in the LCA analysis. Reducing the drying energy from 543 kwh to 380 kwh, the total CED and GWP values for the conventional drying option decreased by about 19.2% (from 7.29 GJ to 5.89 GJ) and 5.3% (from 130 kg $CO_2$ eq to 123 kg $CO_2$ eq), respectively (see Table 5). On the other hand, increasing the drying energy by 30% increased the CED and GWP by about 19.1% and 5.47%, respectively (see Table 5). Similarly, for the HP-assisted drying method, increasing the drying energy (290 kwh) by 30% increased the CED and GWP by about 14.65% and 3.3%, respectively. This indicates that increasing energy use efficiency could improve the sustainability of dried organic apple products.

**Table 5.** Sensitivity analysis results considering dried apple value chain. The values are provided as GJ/FU, kg $CO_2$ eq/FU, and as % of basic scenario.

| Change in Drying Energy | Dried Apple (Conventional Dryer) | | | | Dried Apple (HP-Assisted Dryer) | | | |
|---|---|---|---|---|---|---|---|---|
| | CED | % | GWP | % | CED | | GWP | % |
| (−30%) reduction | 5.89 | 19.20 | 123.00 | 5.30 | 4.37 | 14.65 | 116.00 | 3.30 |
| (−15%) reduction | 6.59 | 9.60 | 127.00 | 2.20 | 4.75 | 7.20 | 118.00 | 1.67 |
| Basic scenario | 7.29 | 0.00 | 129.89 | 0.00 | 5.12 | 0.00 | 120.00 | 0.00 |
| (+15%) increase | 7.98 | 9.47 | 133.00 | 2,39 | 5.50 | 7.40 | 122.00 | 1.67 |
| (+30) increase | 8.68 | 19.10 | 137.00 | 5.47 | 5.87 | 14.65 | 124.00 | 3.30 |

## 4. Discussion

The environmental impacts of agri-food activities are significant and many investigations have been conducted that use the LCA approach. The LCA study results of food value chains could help supply chain actors identify hot-spot stages along the chain for environmental improvements and allow consumers to make environmentally responsible choices when purchasing and consuming food [40]. The use of pesticides, fertilizers, diesel, and electricity contributes most to the environmental impacts of agricultural apple production [41–43].

Regarding the energy demand, the total CED values were 7.29 GJ and 5.12 GJ per FU for the conventional drying and HP-assisted drying methods, respectively. The purpose of identifying an efficient process for the drying of fruits such as organic apples is to reduce food loss and increase product shelf life and food security while improving the environmental and economic performance of the product. For instance, when improving the drying efficiency with the HP-assisted method, the reduction in CED value could be up to 30% when compared to the conventional drying technique. The total GWP value was reduced from 130 kg $CO_2$ eq to 120 kg $CO_2$ eq per FU when conventional drying was replaced with HP-assisted drying.

In this study, when quantifying the GWP and CED impacts without considering the drying process, the values were found to be 265 kg $CO_2$ eq and 6.11 GJ per FU, i.e., 1 ton of fresh apples at the farm gate. This is within the range of reported values in the literature (see Table 2). The LCA study by Notarnicola et al. [32] indicated that fruits have lower environmental impact than other foods. However, the introduction of fruit-drying techniques could have an additional environmental burden. For instance, the findings of the current study indicate that the post-harvest processing and handling stage was found to be an environmental hot-spot (see Figures 4 and 6). The main contributor to the high impact at the post-harvest stage was the drying process followed by packaging activity. Gonçalves and Neto [23] suggested that energy consumption contributes most to the environmental impact of apple dehydration and snack production. According to a study in New Zealand [38], the production of pesticides and the use of machines in apple production contribute significantly to the energy consumption of apple production.

The agricultural sector contributes about 30% of global greenhouse gas (GHG) emissions [1]. In the 27 EU countries, greenhouse gas emissions from agriculture have decreased from about 497 Mt $CO_2$ eq in 1990 to 394 Mt $CO_2$ eq in 2018. If only emissions from Sweden are considered, they decreased from 7.64 Mt $CO_2$ eq to 6.79 Mt $CO_2$ eq. The reduction could be due to improved agricultural activities and efficient use of resources. Organic farming systems enrich soil fertility, avoid industrial fertilizers and pesticides, and increase food quality [44]. In some cases, the low production yield and long transportation (when sourced from long distances) can increase its environmental burden [44]. The environmental impact of food production and consumption is significant and the quantification and communication of these impacts are important activities. Appropriate labeling of food products, communication with consumers, and information-based decisions in the food supply chain management could lead to the improved sustainability of the food sector [45,46]. In this regard, the results from the current LCA study of organic dried apples represent a useful contribution.

According to the findings of the current study, improving apple-drying energy provides a reduction in the environmental burden of the dried apple value chain. Such an improvement could be applicable in the processing of both conventional and organic products. In the current study, the improved energy efficiency in drying apples could reduce the acidification and eutrophication impacts, as the release of the nutrients (causing acidification and eutrophication) during the production of energy could be reduced. In the dried apple value chain, the agricultural stage contributed more to acidification, while the post-harvest processing (including drying) contributed to eutrophication. Eutrophication and acidification impacts are among many environmental impact categories that could be caused by the agri-food sector [16,32]. Excessive levels of nitrogen and phosphorus in soil or water can enter the environment via atmospheric emissions (from road traffic, shipping, power stations, etc.), run-off from agriculture, and discharges from sewage treatment plants and factories, causing eutrophication [47]. Further studies are required to compare the environmental impacts of apple value chains in terms of not only the drying process but also agricultural production methods, e.g., comparing organic and conventional apple production and processing as well as geographical locations. In long supply chains, e.g., imported fruits, transport contributes significantly to GWP, energy demand, and acidification and eutrophication impacts [24].

This study represents an original LCA study that increases our understanding of the influence of the drying process on the environmental footprint in apple value chains. This enables us to improve the energy use efficiency of the drying process. The drying process of fruits such as apples can increase shelf life and reduce FLW along the supply chain. This in turn reduces the environmental burden and nutritional losses associated with FLW. Future LCA studies may extend the investigation to other fruits and/or other study areas.

## 5. Conclusions

The main objective of this study was to assess the environmental impacts of dried organic apple by using a life cycle analysis (LCA) approach. Two options were considered for drying apples: conventional and HP-assisted drying techniques. The main focus was to investigate how the introduction of HP-assisted apple drying could influence the environmental impacts of the organic apple food value chain. In this study, organic apples produced and supplied in Sweden were considered. The LCA was based on a functional unit (FU) of 1 ton of fresh organic apples at the farm stage. The main environmental impact categories investigated in this study were cumulative energy demand (CED), global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP), while the main focus was on CED and GWP. A cradle-to-consumer gate LCA was conducted. Agricultural production, post-harvest activities (such as storing, packaging, and processing), and transport activities were the main life cycle stages used for generating the life cycle impact assessment results.

The findings indicate that the post-harvest processing and handling stage was an environmental hot-spot. In this dried apple value chain, the drying process and packaging contributed more to the environmental impact at the post-harvest stage. Considering the two options for drying organic apple, the total CED value was reduced from 7.29 GJ (conventional drying) to 5.12 GJ (HP-assisted drying method) per FU, i.e., a reduction of about 30%. Similarly, the GWP value was reduced from 130 kg $CO_2$ eq to 120 kg $CO_2$ eq per FU.

HP-assisted drying was also able to reduce the acidification and eutrophication effects of dried apple value chains. The results of the current study enable the generation of new data and knowledge on the environmental impacts of organic apple value chains. In particular, the findings of this study indicate the importance of improving the energy and process efficiency at the post-harvest stage to increase the sustainability of dried organic apple value chains. Therefore, these results could be useful in future studies. In countries like Sweden, which imports about 85% of its apple demand, more LCA studies that compare the local and imported fruit value chains are needed that explore the efficient post-harvest processing and preservation of fruits. The results could also be useful for the decision-making of policy makers and for consumers when making purchasing decisions.

**Funding:** This study is part of the SusOrgPlus project funded via the ERA-NET CORE Organic Cofund from the European Commission's Horizon 2020 Framework Programme for Research and Innovation Contract No. 727495.

**Institutional Review Board Statement:** Not applicable.

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The author declares no conflicts of interest.

## References


1. Foley, J. The Other Inconvenient Truth. TED Talks, Filmed October 2010. 2010. Available online: http://www.ted.com/talks/jonathan_foley_the_other_inconvenient_truth#t-540163 (accessed on 26 October 2015).
2. Gomiero, T. Chapter 2—Organic agriculture: Impact on the environment and food quality. In *Environmental Impact of Agro-Food Industry and Food Consumption*; Academic Press: New York, NY, USA, 2021; pp. 31–58. [CrossRef]
3. Cattaneo, A.; Federighi, G.; Vaz, S. The environmental impact of reducing food loss and waste: A critical assessment. *Food Policy* **2021**, *98*, 101890. [CrossRef]
4. Read, Q.D.; Brown, S.; Cuéllar, A.D.; Finn, S.M.; Gephart, J.A.; Marston, L.T.; Meyer, E.; Weitz, K.A.; Muth, M.K. Assessing the environmental impacts of halving food loss and waste along the food supply chain. *Sci. Total Environ.* **2020**, *712*, 136255. [CrossRef]
5. van der Werf, H.M.G.; Knudsen, M.T.; Cederberg, C. Towards better representation of organic agriculture in life cycle assessment. *Nat. Sustain.* **2020**, *3*, 419–425. [CrossRef]
6. Clark, S. Organic Farming and Climate Change: The Need for Innovation. *Sustainability* **2020**, *12*, 7012. [CrossRef]
7. Jönsson, Å.H. Organic Apple Production in Sweden: Cultivation and Cultivars. Ph.D. Thesis, Department of Crop Science, Faculty of Landscape Planning, Horticulture and Agricultural Science, Swedish University of Agricultural Sciences, Alnarp, Sweden, 2007. ISSN 1652-6880, ISBN 978-9-15767-313-8. Available online: https://pub.epsilon.slu.se/1338/1/%C3%85J_finalversion.pdf (accessed on 20 April 2020).
8. Eurostat. Production of Fruit and Vegetables. 2016. Available online: https://ec.europa.eu/eurostat/documents/2995521/7517627/5-22062016-AP-EN.pdf/8247b23e-f7fd-4094-81ec-df1b87f2f0bb (accessed on 2 February 2024).
9. Roy, P.; Nei, D.; Orikasa, T.; Xu, Q.; Okadome, H.; Nakamura, N.; Shiina, T. A review of life cycle assessment (LCA) on some food products. *J. Food Eng.* **2009**, *90*, 1–10. [CrossRef]
10. Zhang, Z.; Zhao, J.; Hou, L.; Xu, X.; Zhu, Y.; Zhai, B.; Liu, Z. Comparative assessment of environmental impacts, mitigation potentials, and economic benefits of rain-fed and irrigated apple production systems on China's Loess Plateau. *Sci. Total Environ.* **2023**, *869*, 161791. [CrossRef]
11. Goossens, Y.; Annaert, B.; De Tavernier, J.; Mathijs, E.; Keulemans, W.; Geeraerd, A. Life cycle assessment (LCA) for apple orchard production systems including low and high productive years in conventional, integrated and organic farms. *Agric. Syst.* **2017**, *153*, 81–93. [CrossRef]
12. Kai, T.; Adhikari, D. Effect of Organic and Chemical Fertilizer Application on Apple Nutrient Content and Orchard Soil Condition. *Agriculture* **2021**, *11*, 340. [CrossRef]
13. Keyes, S.; Tyedmers, P.; Beazley, K. Evaluating the environmental impacts of conventional and organic apple production in Nova Scotia, Canada, through life cycle assessment. *J. Clean. Prod.* **2015**, *104*, 40–51. [CrossRef]
14. Bartzas, G.; Vamvuka, D.; Komnitsas, K. Comparative life cycle assessment of pistachio, almond and apple production. *Inf. Process. Agric.* **2017**, *4*, 188–198. [CrossRef]
15. Iriarte, A.; Yáñez, P.; Villalobos, P.; Huenchuleo, C.; Rebolledo-Leiva, R. Carbon footprint of southern hemisphere fruit exported to Europe: The case of Chilean apple to the UK. *J. Clean. Prod.* **2021**, *293*, 126118. [CrossRef]
16. Longo, S.; Mistretta, M.; Guarino, F.; Cellura, M. Life Cycle Assessment of organic and conventional apple supply chains in the North of Italy. *J. Clean. Prod.* **2017**, *140*, 654–663. [CrossRef]
17. Vinyes, E.; Asin, L.; Alegre, S.; Muñoz, P.; Boschmonart, J.; Gasol, C.M. Life Cycle Assessment of apple and peach production, distribution and consumption in Mediterranean fruit sector. *J. Clean. Prod.* **2017**, *149*, 313–320. [CrossRef]
18. Ekinci, K.; Demircan, V.; Atasay, A.; Karamursel, D.; Sarica, D. Energy, Economic and Environmental Analysis of Organic and Conventional Apple Production in Turkey. *Erwerbs-Obstbau* **2020**, *62*, 1–12. [CrossRef]
19. Fabbri, S.; Olsen, S.I.; Owsianiak, M. Improving environmental performance of post-harvest supply chains of fruits and vegetables in Europe: Potential contribution from ultrasonic humidification. *J. Clean. Prod.* **2018**, *182*, 16–26. [CrossRef]
20. Jeswani, H.K.; Figueroa-Torres, G.; Azapagic, A. The extent of food waste generation in the UK and its environmental impacts. *Sustain. Prod. Consum.* **2021**, *26*, 532–547. [CrossRef]
21. Loiseau, E.; Colin, M.; Alaphilippe, A.; Coste, G.; Roux, P. To what extent are short food supply chains (SFSCs) environmentally friendly? Application to French apple distribution using Life Cycle Assessment. *J. Clean. Prod.* **2020**, *276*, 124166. [CrossRef]
22. Svanes, E.; Johnsen, F.M. Environmental life cycle assessment of production, processing, distribution and consumption of apples, sweet cherries and plums from conventional agriculture in Norway. *J. Clean. Prod.* **2019**, *238*, 117773. [CrossRef]
23. Gonçalves, I.; Neto, B. A Life Cycle Assessment of Dehydrated Apple Snacks. *Sustainability* **2023**, *15*, 16304. [CrossRef]
24. Frankowska, A.; Jeswani, H.K.; Azapagic, A. Life cycle environmental impacts of fruits consumption in the UK. *J. Environ. Manag.* **2019**, *248*, 109111. [CrossRef] [PubMed]
25. Medici, M.; Canavari, M.; Toselli, M. Interpreting Environmental Impacts Resulting from Fruit Cultivation in a Business Innovation Perspective. *Sustainability* **2020**, *12*, 9793. [CrossRef]
26. Le Féon, S.; Benezech, T.; Bris, G.Y.-L.; Aubin, J.; Sampers, I.; Herreman, D.; Pénicaud, C. Life cycle assessment of a small-scale and low-input organic apple value chain including fresh fruit, juice and applesauce. *Clean. Environ. Syst.* **2023**, *11*, 100141. [CrossRef]
27. Reynolds, C.J.; Buckley, J.D.; Weinstein, P.; Boland, J. Are the Dietary Guidelines for Meat, Fat, Fruit and Vegetable Consumption Appropriate for Environmental Sustainability? A Review of the Literature. *Nutrients* **2014**, *6*, 225–2265. [CrossRef]

28. PRé Consultants. SimaPro Database Manual, Version 2.9. 2015. Available online: https://www.pre-sustainability.com/download/DatabaseManualMethods.pdf (accessed on 17 January 2017).
29. Frischknecht, R.; Wyss, F.; Knöpfel, S.B.; Lützkendorf, T.; Balouktsi, M. Cumulative energy demand in LCA: The energy harvested approach. *Int. J. Life Cycle Assess* **2015**, *20*, 957. [CrossRef]
30. *ISO 14040:2006*; Environmental Management, Life Cycle Assessment Principles and Framework. International Organization for Standardization: Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 28 February 2024).
31. *ISO 14044:2006*; Environmental Management, Life Cycle Assessment Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006. Available online: https://www.iso.org/standard/38498.html (accessed on 28 February 2024).
32. Curran, M.A. Life cycle assessment in the agri-food sector: Case studies, methodological issues, and best practices. *Int. J. Life Cycle Assess* **2016**, *21*, 785–787. [CrossRef]
33. Johansson, D. Life Cycle Assessment (LCA) of Apples—A Comparison between Apples Produced in Sweden, Italy and Argentina. Master's Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2015. Available online: https://stud.epsilon.slu.se/8390/17/johansson_d_150922.pdf (accessed on 12 January 2018).
34. Stadig, M. Life Cycle Analysis of Apple Production. Case Study for Sweden, New Zeeland, and France. SIK Report No 683. 2001. Available online: https://www.diva-portal.org/smash/get/diva2:959114/FULLTEXT01.pdf (accessed on 6 January 2020).
35. SINTEF Energy Research, Norway. 2020. Available online: https://sintef.brage.unit.no/sintef-xmlui/handle/11250/3077573 (accessed on 2 December 2023).
36. Omoleye, O. Assessment of Food Losses and Waste and Related Greenhouse Gas Emissions Along a Fresh Apples Value Chain. Master's Thesis, Swedish University of Agricultural Sciences, Uppsala, Sweden, 2020. Available online: https://stud.epsilon.slu.se/16253 (accessed on 2 April 2021).
37. Csaki, D.; Rudolfsson, A. Internal Logistics Solutions for Äppelriket. Högskolan Kirstianstad. 2005. Available online: https://researchportal.hkr.se/ws/portalfiles/portal/35123933/FULLTEXT01.pdf (accessed on 15 January 2023).
38. Curran, M.A. *Life Cycle Assessment Student Handbook*; Wiley, Scrivener Publishing: New York, NY, USA, 2015; ISBN 978-1-11908-354-2.
39. Karlsson, H. Seasonal Vegetables: An Environmental Assessment of Seasonal Food. Master's Thesis, Norwegian University of Life Sciences, Ås, Norway, 2011. Available online: https://core.ac.uk/download/pdf/30889678.pdf (accessed on 2 November 2020).
40. Milà i Canals, L.; Burnip, G.M.; Cowell, S.J. Evaluation of the environmental impacts of apple production using Life Cycle Assessment (LCA): Case study in New Zealand. *Agric. Ecosyst. Environ.* **2006**, *114*, 226–238. [CrossRef]
41. Alaphilippe, A.; Boissy, J.; Simon, S.; Godard, C. Environmental impact of intensive versus semi-extensive apple orchards: Use of a specific methodological framework for Life Cycle Assessments (LCA) in perennial crops. *J. Clean. Prod.* **2016**, *127*, 555–561. [CrossRef]
42. Cheng, J.; Wang, Q.; Li, D.; Yu, J. Comparative Analysis of Environmental and Economic Performance of Agricultural Cooperatives and Smallholder Farmers for Apple Production in China. *Agriculture* **2022**, *12*, 1281. [CrossRef]
43. Zhu, Z.; Jia, Z.; Peng, L.; Chen, Q.; He, L.; Jiang, Y.; Ge, S. Life cycle assessment of conventional and organic apple production systems in China. *J. Clean. Prod.* **2018**, *201*, 156–168. [CrossRef]
44. Raghu, K.C. Comparative Lifecycle Assessment on Organic and Conventional Carrots-Case: Carrots from South-Savo and Imported Carrots from Italy. Master's Thesis, Faculty of Technology, Lappeenranta University of Technology, Lappeenranta, Finland, 2014. [CrossRef]
45. Stoessel, F.; Juraske, R.; Pfister, S.; Hellweg, S. Life cycle inventory and carbon and water footprint of fruits and vegetables: Application to Swiss retail. *Environ. Sci. Technol.* **2012**, *46*, 3253–3262. [CrossRef] [PubMed]
46. Le Féon, S.; Benezech, T.; Bris, G.Y.-L.; Aubin, J.; Sampers, I.; Herreman, D.; Pénicaud, C. Datasets for the environmental assessment of an apple value chain including fresh fruits, juice and applesauce from an organic low-input production farm. *Data Brief* **2023**, *51*, 109824. [CrossRef] [PubMed]
47. Swedish Environmental Protection Agency. Swedish Environmental Objectives. Available online: https://www.naturvardsverket.se/en/om-miljoarbetet/swedish-environmental-objectives/ (accessed on 15 January 2023).