EAEF Engineering in Agriculture, Environment and Food
published by AABEA
Research Article

EAEF 16 (1) : 1−14, 2023

Life cycle assessment of apple exported from Japan to Taiwan and potential environmental impact abatement

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Abstract

A life cycle assessment (LCA) was performed for fresh apples exported from Japan to Taiwan to identify hotspots along the supply chain. We further explore how to minimize the environmental impact of the post-harvest chain to mitigate the carbon footprint of the apple chain. Within the climate change impact category, the hotspots were cultivation and truck transport with cooling in Japan. Based on the hotspots, introducing a modal shift in Japanese domestic transportation and changing to a port closer to the farm for ship distribution would decrease the climate change impact by 13−22 % relative to the base case. This study provided essential insights for the development of a more environmentally friendly apple distribution process from Japan to Taiwan.

[Keywords] apple export from Japan, life cycle assessment, carbon footprint, hotspot analysis, process optimization

1. Introduction

In March 2020, the Japanese government targeted an expansion of agricultural, forestry, fishery and food product exports to 5 trillion yen by 2030 (MAFF, 2020a). The Japanese government recognizes apples as a promising target for expanding agricultural product exports (MAFF, 2016a) because Japanese apples are recognized by consumers in East Asian countries as very high-quality apples (sweet taste, attractive texture, scent, and color) (Aomori Prefecture, 2018; Huang, 2015). Apple exports have been increasing since 2012 and reached 35,888 t in 2019 (MAFF, 2020b). Taiwan is the largest destination for apples exported from Japan. Consumers in Taiwan prefer Japanese apples for gift purposes or as offerings to Buddhist gods during the Chinese New Year season. The price of apples imported from Japan is 2−3 times higher than that of apples imported from other countries, such as the USA, Chile, and New Zealand. Despite this high price, apple exports from Japan to Taiwan are increasing because consumers in Taiwan favor the quality of Japanese apples.

In Japan, apples are usually harvested in autumn from September to November. After harvest, apples are stored in low-temperature (LT) storage (for apples distributed by March) and controlled-atmosphere (CA) storage (for apples distributed from March to August) to ensure a year-round supply. Both LT and CA storage require considerable energy use because the fruits are stored for long periods (Gwanpua et al., 2015; McCormick et al., 2010; 2012).

In fact, each step of the apple postharvest process, such as storage (LT or CA), packaging, and distribution, comes with an energy cost and includes resource, material and water use, possibly complemented with apple losses by postharvest decay. According to the Strategy for Sustainable Food System (MAFF, 2021), Green House Gasses (GHGs) from agricultural sectors account for approximately 25 % of the total emissions in the world. In Japan, the previous prime minister, Suga, determined to reduce GHGs by 46 % by 2030 compared to the gases emitted in 2013 and to achieve zero emission (carbon neutral) by 2050; we are required to take practical actions for GHG reduction.

Boschiero et al. (2019) analyzed greenhouse gas emissions and energy requirements in post-harvest of apples in Northern Italy by life cycle assessment and concluded that the most favorable environmental performances were storage by CA, delivering fruits in large reusable plastic bins, and their transport over short distances. In addition, there are many previous studies related to life cycle analysis in apple production processes in European countries (Cerutti et al., 2013; Goossens et al., 2017; Longo et al., 2017), USA (Smith and Lal, 2022), Canada (Keyes et al., 2015), and China (Zhu et al., 2018). However, information on the environmental burden of fresh apple distribution processes from Japan to Taiwan throughout the apple life cycle has, as far as the authors are aware, not yet been collected in a systematic way, and there are no previous studies discussing the options to decrease the environmental burdens of the distribution process. Therefore, in this study, a life cycle assessment (LCA) for fresh apples exported from Japan to Taiwan was conducted. The environmental hotspots of the apple life cycle were identified, and the

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main focus will lie on the possibilities for environmental burden abatement in the post-harvest distribution chain.

2. Methodology

2.1. Goal definition and scope

The goal of this study is threefold: (1) quantify the environmental burden of apples exported from Japan to Taiwan by life cycle assessment (LCA) methodology; (2) identify the hotspots for the climate change impacts of the fresh apple life cycle; and (3) determine how to minimize the environmental impact of the distribution process and reduce the associated climate change impacts. The apple chain under study refers to the cultivar "Fuji", which corresponds to 47.1 % of the total amount of apples exported to Taiwan (Ishitsuka, 2017).

2.2. Functional unit

As a reference unit, a mass based functional unit (FU) was chosen, namely, 1 kg-fresh apple ready for sale in Taiwan. This requires an estimated 1.375 kg of fresh apple to be harvested in Japan due to losses in the chain, as will be explained in more detail in section 2.3. below. According to the Apple Commercial Cooperatives Federation in Aomori Prefecture (2019), 92 % of the apples exported from Japan to Taiwan were stored using LT technology, whereas 8 % underwent CA storage. Using this percentage distribution, our apple chain was modeled accordingly.

2.3. Inventory analysis, data collection and system boundaries

The life cycle inventory analysis quantifies resource use, energy use, and environmental emissions associated with the evaluated system. Figure 1 shows the flow diagram of the distribution channels for exporting fresh apples to Taiwan. The process flow was determined from an interview with the Japanese apple supplier "Tsugaru Hirosaki Agricultural Cooperative, Japan". The system boundaries include cultivation and harvest, as well as postharvest processes such as sorting, packaging and storing, and transport up until the final point of sale. The quantitative parameters of these processes are included in Tables 1–3. These are based on our own measurements and interviews with actors along the apple chain, complemented with data taken from the literature and from the Japanese LCA software "MiLCA ver. 2.2" (Sustainable Management Promotion

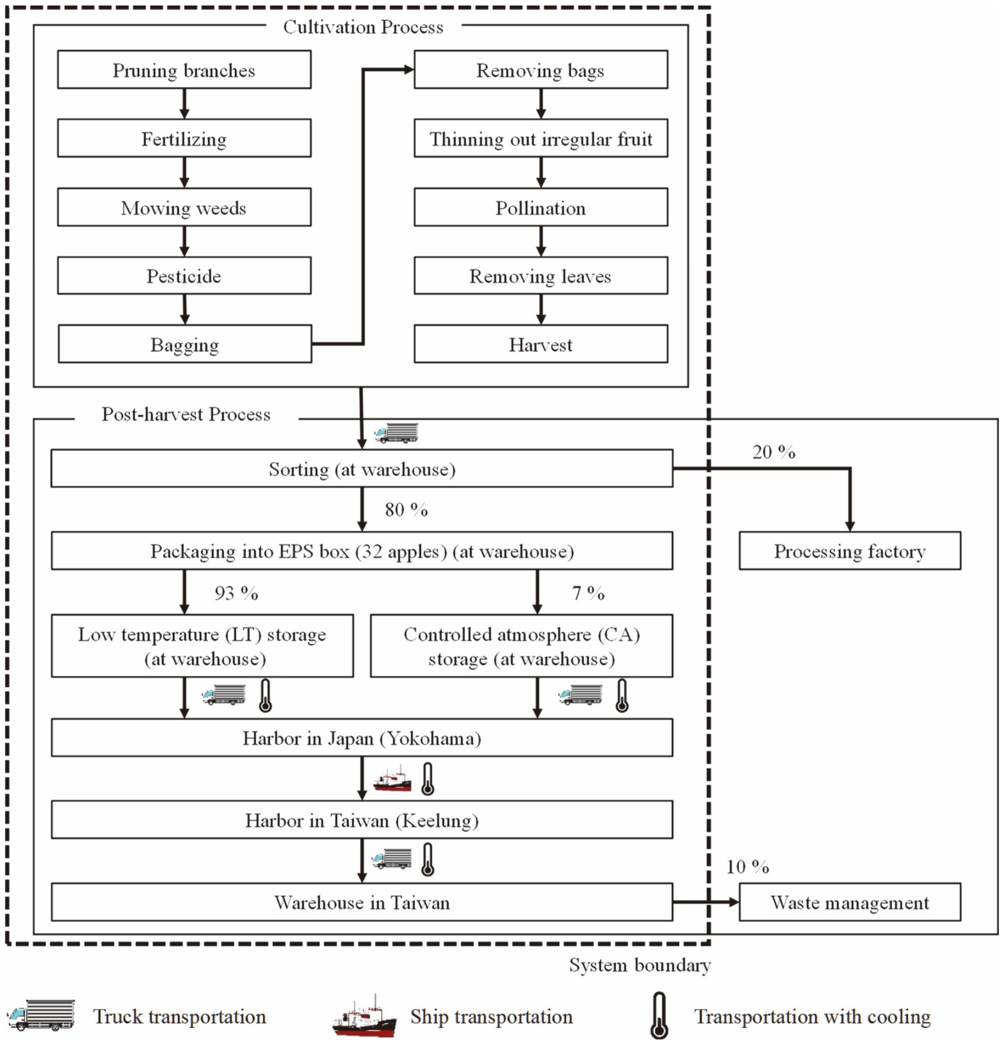


Fig. 1 Flow diagram of fresh apple distribution channels for export to Taiwan

Table 1 Process details and assumption conditions for apple cultivation process (average yield [2]= 20.0 t apple/ha), expressed per kg harvested apple

Cultivation processes [1]	Consumed materials	Value	Unit	Source	Characteristics and assumption conditions
Fertilizing	Nitrogen fertilizer	Cannot be disclosed [3]	kg-N/kg-fresh apple	IDEA ver.2 Database [2]	Average value in Japan
Fertilizing	Phosphatic fertilizer	Cannot be disclosed [3]	kg-P_2O_5/kg-fresh apple	IDEA ver.2 Database [2]	Average value in Japan
Fertilizing	Potassium fertilizer	Cannot be disclosed [3]	kg-K_2O/kg-fresh apple	IDEA ver.2 Database [2]	Average value in Japan
Mowing weeds, pesticide, harvest	Heat energy, light oil	Cannot be disclosed [3]	L/kg-fresh apple	IDEA ver.2 Database [2]	Average value in Japan
Mowing weeds, pesticide, harvest	Heat energy, heavy oil	Cannot be disclosed [3]	L/kg-fresh apple	IDEA ver.2 Database [2]	Average value in Japan
Mowing weeds, pesticide, harvest	Heat energy, petroleum	Cannot be disclosed [3]	L/kg-fresh apple	IDEA ver.2 Database [2]	Average value in Japan
Pesticide	Pesticide, carbaryl	0.003311 kg/kg-fresh apple		Aomori prefecture (2019a, 2019b)	
Pesticide	Disinfectant, captan	0.002600 kg/kg-fresh apple		Aomori prefecture (2019a, 2019b)	
Pesticide	Herbicide	0.002536 kg/kg-fresh apple		Aomori prefecture (2019a, 2019b)	
Bagging	Waxed paper	0.002200 kg/kg-fresh apple		Interview for Shibataya Kakohshi Co. Ltd.	
Harvest (electricity in temporally warehouse)	Electricity	Cannot be disclosed [3]	kWh/kg-fresh apple	IDEA ver.2 Database [2]	Average value in Japan
Harvest (plastic box to collect apples)	Polypropylene	0.001590 kg/kg-fresh apple		Web site of Rakuten, Inc.	
All processes in cultivation	Water	Cannot be disclosed [3]	m^3 / kg-fresh apple	IDEA ver.2 Database [2]	Average value in Japan

1) Pruning branches, fertilizing, trimming out irregular fruit, pollination, bagging, and removing leaves processes are conducted by human power. The energy consumptions for making devices used in these process (such as mowing machine, sprayer, shear for pruning branches, and so on are not included.

2) IDEA ver.2 Database (Inventory Database for Environmental Analysis), accessed through MiLCA software ver. 2.2 (AIST and SuMPO, Japan)

3) The data utilization rules of the IDEA database prohibit the directly use of the values in any publications.

Organization (SuMPO), Japan), as described below.

2.3.1. Cultivation

The cultivation process includes pruning branches, fertilizing, mowing weeds, using pesticides, bagging, removing bags, trimming irregular fruit, pollination, removing leaves, and harvesting. Many growers in Japan cover apples with paper bags one by one to protect them from disease and pests and promote coloring and longer storage life. During harvest, apples are put into plastic harvest containers (PP, W 644 mm × D 320 mm × H 294 mm (outer size), 0.0476 m^3 (effective capacity), 2.22 kg) and are transported from the orchard to the warehouse. The estimated apple bulk density is 293.21 kg m^{-3} (Ambaw et al., 2016). The harvest containers can be used 100 times based on an interview with the “Tsugaru Hirosaki Agricultural Cooperative, Japan”. Transport and washing steps for reuse of containers were excluded from the boundary because these conditions were heavily dependent on cultivars. In Japan, apples are produced mainly in the northeast regions, especially in the Aomori Prefecture. The annual production in Aomori Prefecture in 2014 was 468,000 t (MAFF, 2016b), which accounted for over 50 % of the total apple production in Japan. Therefore, we assumed that apples were produced in Aomori Prefecture and distributed from there. The input data for the cultivation process, such as energy, water, fertilizers, pesticides, and other materials for agricultural use, were based on the data “production of apple” in the IDEA ver2 inventory database available in MiLCA software ver. 2.2. The apple cultivation process in the IDEA database (National Institute of Advanced Industrial Science and Technology (AIST) and SuMPO, Japan) was considered as a mixture of young, fully productive and old orchards. Carbaryl and captan were chosen as pesticide and disinfectant materials for the calculation of

Table 2 Process details and assumption conditions for apple postharvest process, expressed per kg harvested apple

Post harvest processes	Consumed materials	Value Unit	Source	Characteristics and assumption conditions
Sorting	Electricity	0.00144 kWh/kg-fresh apple	Interview with Kubota Co. Ltd.	1,800 apples/h
LT Storage	Electricity	0.01137 kWh/kg-fresh	Duiven and Binard, 2002	1 ℃, 2.0 months
CA Storage	Electricity	0.01966 kWh/kg-fresh apple/month	Kittemann et al., 2015	1 ℃, 0.7 kPaO_2 + 1.5 kPaCO_2, 5.0 months
Packaging for fresh apple	−	−	−	By human power
Expanded polystyrene box for fresh apple	Expanded polystyrene	0.032089 kg/kg-fresh apple	Measurement	
Cushion material for fresh apple	Polyethylene	0.002533 kg/kg-fresh apple	Measurement	
Plastic bag for covering contents in the EPS box	Polypropylene	0.001554 kg/kg-fresh apple	Measurement	430 W×360 D×150 H, 32 fresh apples/box
Drying agent for fresh apple	Silica gel	0.006528 kg/kg-fresh apple	Measurement	(0.370 kg/one apple)
Sealed tape for EPS box	Polypropylene	0.0004974 kg/kg-fresh apple	Measurement	
Cushion material for EPS box	Corrugated board	0.004222 kg/kg-fresh apple	Measurement	
Cushion material for EPS box	Linerboard	0.01436 kg/kg-fresh apple	Measurement	

Table 3 Process details and assumption conditions for apple transport process

Transport processes	Consumed materials	Value Unit	Source	Characteristics and assumption conditions
Transport fresh apple from farm to warehouse	Transport of light commercial vehicle	12.1 km	NAVITIME (https://www.navitime.co.jp/)	Transport by 1.5 t truck; exclusion of return journeys
Transport fresh apple from warehouse to Yokohama	Transport of lorry with refrigeration machine, 7.5-16 t	720.6 km	NAVITIME (https://www.navitime.co.jp/)	Transport by 8 t truck with refrigeration
Transport fresh apple from Yokohama to Keelung	Transport of ship with cooling	2,089 km	MARINE VESSEL TRAFFIC (http://www.marinevesseltraffic.com /2013/07/distance-calculator.html)	Transport by ship with refrigeration
Transport fresh apple from Keelung to warehouse in Taiwan	Transport of lorry with refrigeration machine, 7.5-16 t	5.4 km	Google (https://www.google.co.jp/maps)	Transport by 8 t truck with refrigeration
Transport dried apple from Keelung to warehouse in Taiwan	Transport of lorry, 7.5-16 t	5.4 km	Google (https://www.google.co.jp/maps)	Transport by 8 t truck

LCA, respectively, based on the information reported by Aomori Prefecture (Aomori Prefecture, 2019a; 2019b).

Emissions from fertilizer and pesticides to air and water were considered by using the data in the IDEA database and the formulae listed in Goossens et al. (2017), as described in Appendix A (Table S1−S3). Please note that the production of agricultural machines such as speed sprayers or mowers, NH_3 emissions to air, and phosphorus emissions to water were not considered in the IDEA database and were therefore not included in our study. As stated in the introduction, the main focus of this study is on the environmental impact reduction in the postharvest chain, and further studies with a focus on LCA inventory data and emission models related to the apple production process in Japan are needed.

2.3.2. Sorting

Apples are transported in plastic harvest containers (see cultivation process) from farms to a nearby warehouse using a small (non-refrigerated) truck. At the warehouse, apples are sorted and evaluated for quality (color and shape) and size by a sorting machine. Those evaluated as “excellent (10 %)”, “very good (50 %)”, and “good (20 %)” are further distributed as fresh apples (MAFF, 2008). Apples evaluated as “not good (20 %)” in the sorting process have low commercial value as fresh apples. They are directed to processing factories for the production of juice, jam, dried products, and confections and out of scope of this study because (i) the environmental impact (for example, related to heating steps) varies for these different types of products and because (ii) they are not destined for export as fresh eating apples. The sorting results imply that to obtain 1 kg of fresh apples exported to Taiwan, 1.25 kg of apples should be harvested.

2.3.3. Postharvest processing: storage and packaging

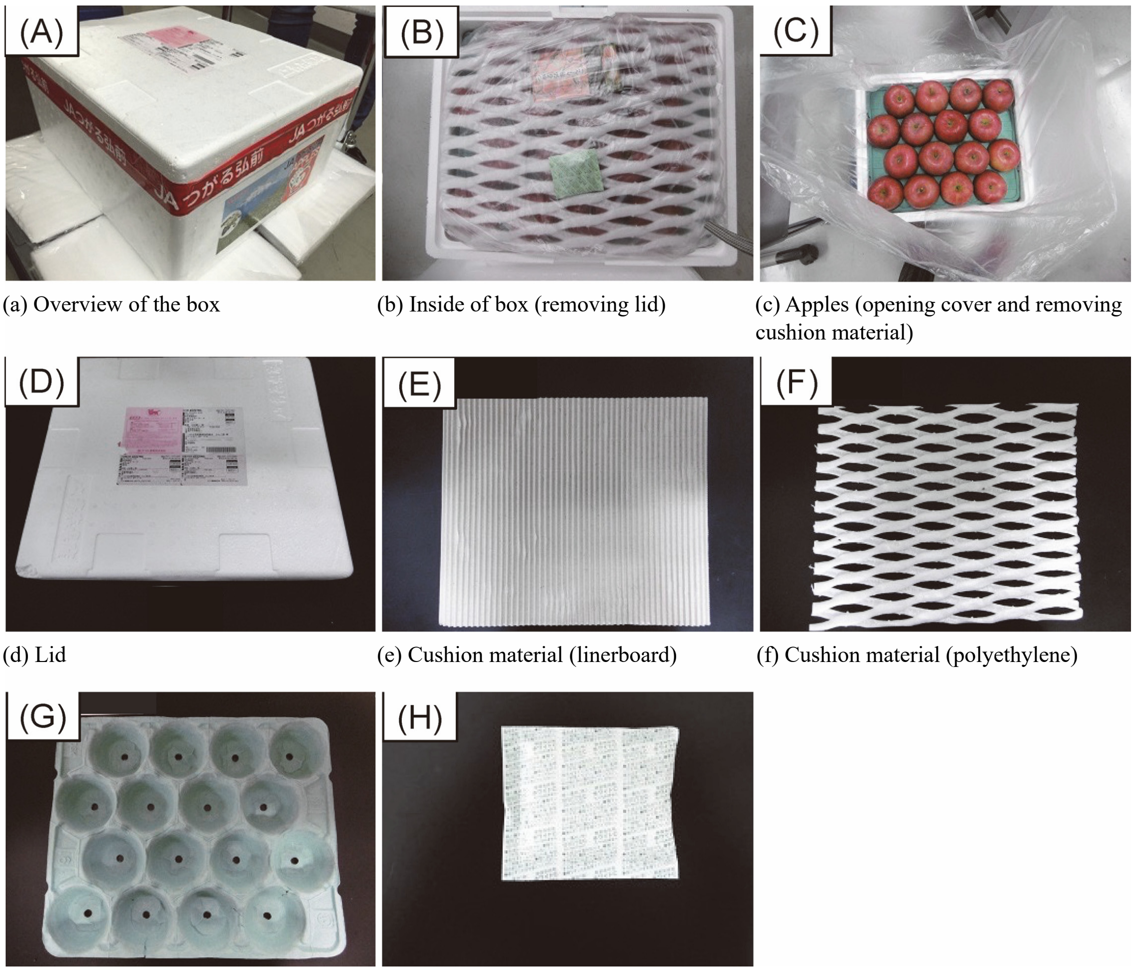
After sorting, the apples destined for fresh consumption are packed into expanded polystyrene (EPS) boxes that fit 32 apples and distributed to warehouses for storage. To obtain detailed insights into the packaging materials used, we purchased an EPS box (including 32 apples) from the Japanese apple supplier “Tsugaru Hirosaki Agricultural Cooperative, Japan” and weighed the different packaging materials used. The packaging materials are shown in Fig. 2. The packaging materials mainly consisted of an EPS box, cushion materials (polyethylene (PE) and paper board), and sealed tape on the EPS box (polypropylene (PP)). Additionally, a package of drying agent (silica gel) is used to preserve the fruits. Exported apples are usually packaged manually (according to an interview with Tsugaru Hirosaki Agricultural Cooperative, Japan); thus, electricity input is not needed for this step. The storage periods under LT and CA were obtained from interviews with the Tsugaru Hirosaki Agricultural Cooperative, Japan, and these values were 2.0 and 5.0 months, respectively.

2.3.4. Shipment to Taiwan

Apples are first transported by truck with cooling from the warehouse in Aomori to Yokohama port (720.6 km). Next, they are shipped to Keelung Harbor in Taiwan over a distance of 2,089 km (refrigerated shipment), after which they are further distributed by truck with cooling (5.4 km) to a Taiwanese warehouse in Taipei Central after which they are ready for sale. Consistent with the study from Shiina (2001), we assume a 10 % loss of fresh apples during the whole distribution from Japan to Taiwan. Therefore, 1.375 kg of fresh apple harvested in Japan is required to obtain 1 kg of fresh apple ready for sale in Taiwan.

2.4. Impact assessment methodology and impact categories

Many LCA research studies have used midpoint methods to model inventory data because of the reliability of their scientific background (Curran, 2017). Therefore, in this study, the International Reference Life Cycle Data system (ILCD) 2011 and the midpoint method from SimaPro 9.0 were chosen. The ILCD method was chosen over existing LCA impact assessment methods in Japan, such as LIME, which is an



(a) Overview of the box (b) Inside of box (removing lid) (c) Apples (opening cover and removing cushion material)
(d) Lid (e) Cushion material (linerboard) (f) Cushion material (polyethylene)
(g) Cushion material (paperboard) (h) Drying agent

Fig. 2 Pictures of packaging materials set for fresh apples box endpoint method. The ILCD method expresses results in the following 16 impact categories: climate change (CC, kg CO_2 eq); ozone depletion (OZ, kg CFC-11 eq); human toxicity, non-cancer effects (HTN, CTUh); human toxicity, cancer effects (HTC, CTUh); particulate matter (PM, kg PM2.5 eq); ionizing radiation HH (IRH, kBq U235 eq); ionizing radiation E (interim) (IRE, CTUe); photochemical ozone formation (PO, kg NMVOC eq); acidification (AC, molc H+ eq); terrestrial eutrophication (TEU, molc N eq); freshwater eutrophication (FEU, kg P eq); marine eutrophication (MEU, kg N eq); freshwater ecotoxicity (FET, CTUe); land use (LU, kg C deficit); water resource depletion (WD, m^3 water eq); and mineral, fossil and renewable resource depletion (MD, kg Sb eq).

The analysis methodology was based on Goossens et al. (2017). First, we created a file for each input in SimaPro containing the applied product and consumed materials. Next, using output data from the ecoinvent v3.2 and Agri-footprint 2.0 databases available in SimaPro 9.0 (PRé Sustainability B.V., the Netherlands), we calculated the impacts associated with applying 1 unit of each input (across the 16 impact categories). These impacts were subsequently imported into Microsoft Excel 2016 and multiplied by the amounts of inputs applied in our system (as listed in the inventory Tables 1−3, and the associated emissions given in Tables S1−S3 (Appendix A)).

Normalized values were calculated to identify the impact categories to which the analyzed system contributes the most (EC-JRC, 2010). This was done by dividing the midpoint impacts by reference impact values — the so-called normalization factors (EU 27) — given by Sala et al. (2015). A contribution analysis of the midpoint impacts was subsequently performed for those 5 impact categories with the highest normalized values.

Following the importance of the climate change (CC) impact category in the general sustainability debate, the carbon footprint of our apple supply chain was analyzed in depth, and hotspots were identified. The hotspots were hereby defined as those stages cumulatively contributing to at least 50 % of the characterized result for the CC impact. Following the identification of these hotspots, we make suggestions on how to minimize the environmental impact of the fresh apple chain under study and reduce the carbon footprint of our export apple.

Aomori Prefecture (2020) proposed that a conversion of the distribution mode from truck to rail or ship is an important countermeasure to decrease CO_2 emissions. MLIT (2023) reported that rail transport will contribute to CO_2 emission reduction in the distribution sector because the CO_2 emissions of rail transport per 1 km distribution are one-eleventh that of truck transport. The Aomori Port Internationalization Committee (2003) also suggested that promoting the use of local ports such as Aomori port will be expected to decrease environmental loads based on decreasing truck transportation. Therefore, in this study, three alternative scenarios ((B) train case, (C) minimum distance for road transport, (D) middle case) were constructed to discuss the possibility of reducing the carbon footprint in the apple distribution compared with the base case. The transportation distances from Japan to Taiwan in each scenario are shown in Fig. 3. Most parameters of the post-harvest process such as container size and transit time, were retained from the base case; only parameters directly related to the transport mode and the distances traveled were adapted.

3. Results and discussion

3.1. Contribution analysis for the most relevant impact categories

Table 4 lists the total impact of the apple chain across the 16 impact categories, as well as the impacts of each life cycle stage. Figure 4 shows the normalized results of the apple exported from Japan to Taiwan. The impact categories HTN, HTC, MEU, FET, and MD were found to be the five most relevant in our study.

Figure 5 and Table 5 show how each life cycle stage contributed to the characterized results in the five most relevant impact categories.

The cultivation process accounted for up to 99 % of the chosen impact categories, with the largest contribution observed in the MEU impact category, following the FET (89 %), HTC (55 %), and CC (42 %) impact categories (Table 5). A closer look at the cultivation stage (Fig. 6) shows that these impacts were mainly caused by pesticide use, herbicide use, emission of materials, and light fuel oil use. Packaging also accounted for up to 42 % of the chosen impact categories and presented a large contribution to the HTN (43 %) impact categories (Table 5). The greatest contributor to these packaging impacts is polystyrene (66 %) (Fig. 7). The 8 t truck transport (transport from warehouse to port) accounted for up to 64 % of the chosen impact categories following the use of diesel, and it presented a large contribution to MD (64 %, Table 5). Ship transport accounted for up to 20 % of the chosen impact categories following the use of heavy oil, and it presented a large contribution to MD (20 %, Table 5). Negative values of environmental loads were confirmed in the characterized results of some impact categories (Fig. 5−7). The reasons for the negative values in the HTN, HTC, and MD impact categories were electricity generation by the nuclear fuel cycle, removal of toxic materials by the water purification process, reduced toxicity by spoil from coal mining, and refining minerals such as copper or zinc.

3.2. Carbon footprint hotspots

The cultivation and transportation within Japan from the warehouse to port (8 t truck transport) largely contributed to the characterized result in the CC impact category (Table 5). Overseas shipping to Taiwan presented a smaller contribution than domestic truck transport within Japan. This contrasts with

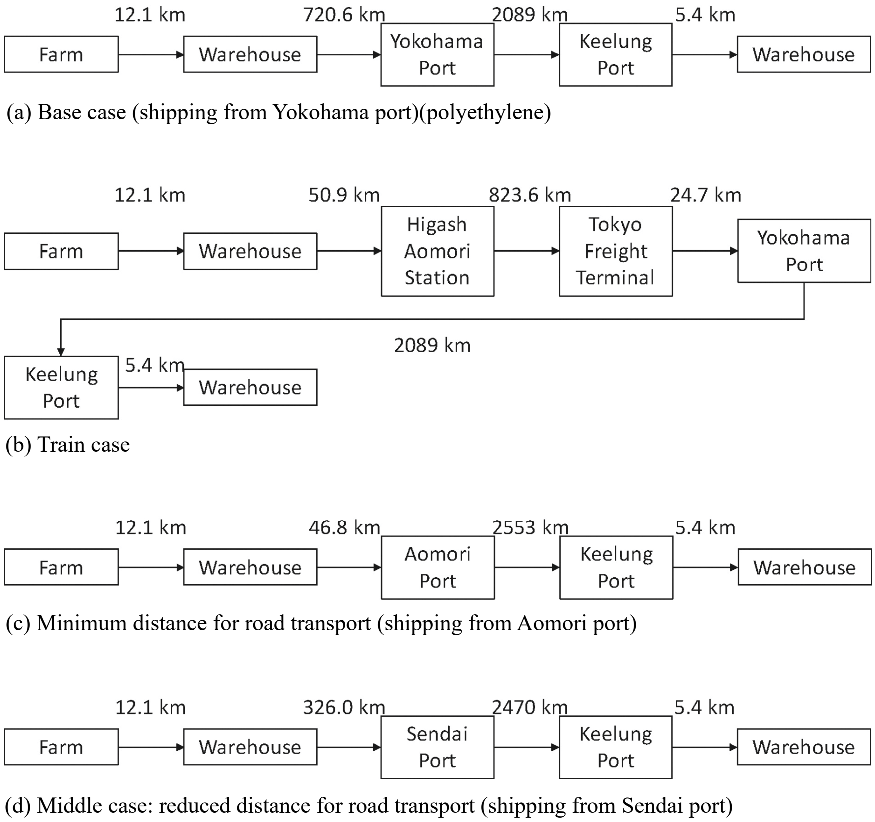


Fig. 3 Chain optimization, focusing on domestic transport, showing the distances of each distribution mode during the apple export chain from Japan to Taiwan

Table 4 Characterized results of the apple export process from Japan to Taiwan, expressed per 1 kg-fresh apple ready for sale in Taiwan

Impact categories	Unit	Total	Culti-vation total	Sorting process	LT storage	CA storage	Package material	Transport from farm to ware house	Transport from ware house to port	Ship transport	Transport in Taiwan
CC	$\times10^{-1}$ kg CO_2 eq	9.20	3.82	0.01	0.19	0.06	2.00	0.27	2.28	0.54	0.02
OZ	$\times10^{-7}$ kg CFC-11 eq	2.28	0.76	0.00	0.01	0.00	0.03	0.05	1.29	0.13	0.01
HTN	$\times10^{-7}$ CTUh	1.48	0.34	0.00	0.02	0.01	0.62	0.10	0.33	0.06	0.00
HTC	$\times10^{-8}$ CTUh	4.28	2.37	0.00	0.05	0.01	0.78	0.16	0.73	0.17	0.01
PM	$\times10^{-4}$ kg PM2.5 eq	5.28	1.94	0.01	0.09	0.03	1.65	0.19	0.79	0.58	0.01
IRH	$\times10^{-2}$ kBq U235 eq	6.08	3.94	0.01	0.08	0.03	−0.21	0.24	1.55	0.44	0.01
IRE	$\times10^{-7}$ CTUe	5.72	4.34	0.00	0.04	0.01	−0.03	0.13	0.98	0.25	0.01
PO	$\times10^{-3}$ kg NMVOC eq	2.97	0.91	0.00	0.05	0.02	0.55	0.15	0.44	0.83	0.00
AC	$\times10^{-3}$ molc H+ eq	4.94	2.20	0.01	0.12	0.04	0.71	0.15	0.63	1.06	0.00
TEU	$\times10^{-2}$ molc N eq	1.09	0.46	0.00	0.02	0.01	0.12	0.05	0.12	0.32	0.00
FEU	$\times10^{-4}$ kg P eq	1.01	0.23	0.00	0.03	0.01	0.43	0.05	0.19	0.06	0.00
MEU	$\times10^{-2}$ kg N eq	4.80	4.73	0.00	0.00	0.00	0.01	0.00	0.01	0.03	0.00
FET	CTUe	49.93	44.44	0.01	0.07	0.02	2.70	0.32	2.03	0.32	0.02
LU	kg C deficit	1.36	0.19	0.00	0.03	0.01	0.21	0.08	0.71	0.13	0.01
WD	$\times10^{-2}$ m^3 water eq	1.21	1.17	0.00	0.00	0.00	0.03	0.00	0.00	0.00	0.00
MD	$\times10^{-5}$ kg Sb eq	2.88	0.21	0.00	0.01	0.00	0.07	0.16	1.85	0.57	0.01

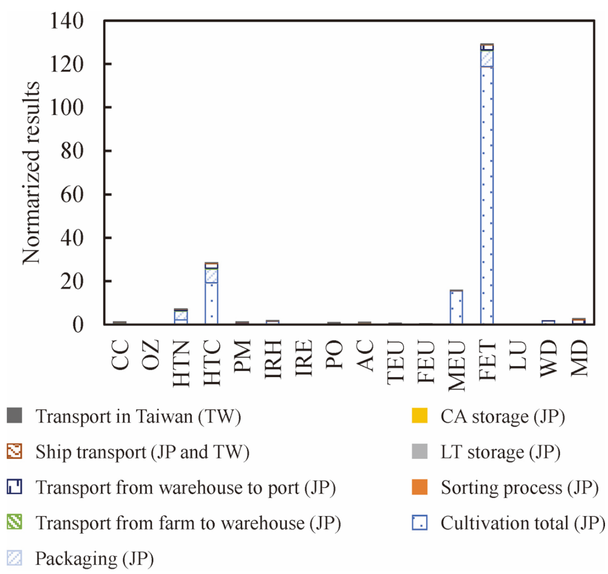
the results in Goossens et al. (2019), where overseas transport of fresh apples from New Zealand to Belgium largely dominated in all impact categories, reflecting the long route of approximately 30 days and more than 20,000 km.

The most relevant process or hotspot within our apple chain was cultivation (42 %). Many previous studies (Cerutti et al., 2013; Goossens et al., 2019; Longo et al., 2017) have also reported high environmental burdens in the cultivation processes of agricultural products stemming from the use of fertilizers, pesticides, and fossil fuels. Therefore, the development of apple cultivation processes with low fertilizer, pesticide, and fossil fuel use is of high importance for reducing the carbon footprint of the apple chain, under the condition that the orchard yield is not affected (as the inputs are expressed per kg fresh weight, as in Table 1). A second hotspot in the apple chain is refrigerated 8 t truck transport within Japan, which is responsible for 25 % of the climate change impact. In the following sections, we explore two scenarios for optimizing the post-harvest stage by addressing the Japanese domestic transport.

3.3. Reducing the carbon footprint: Possibility of process optimization in apple distribution

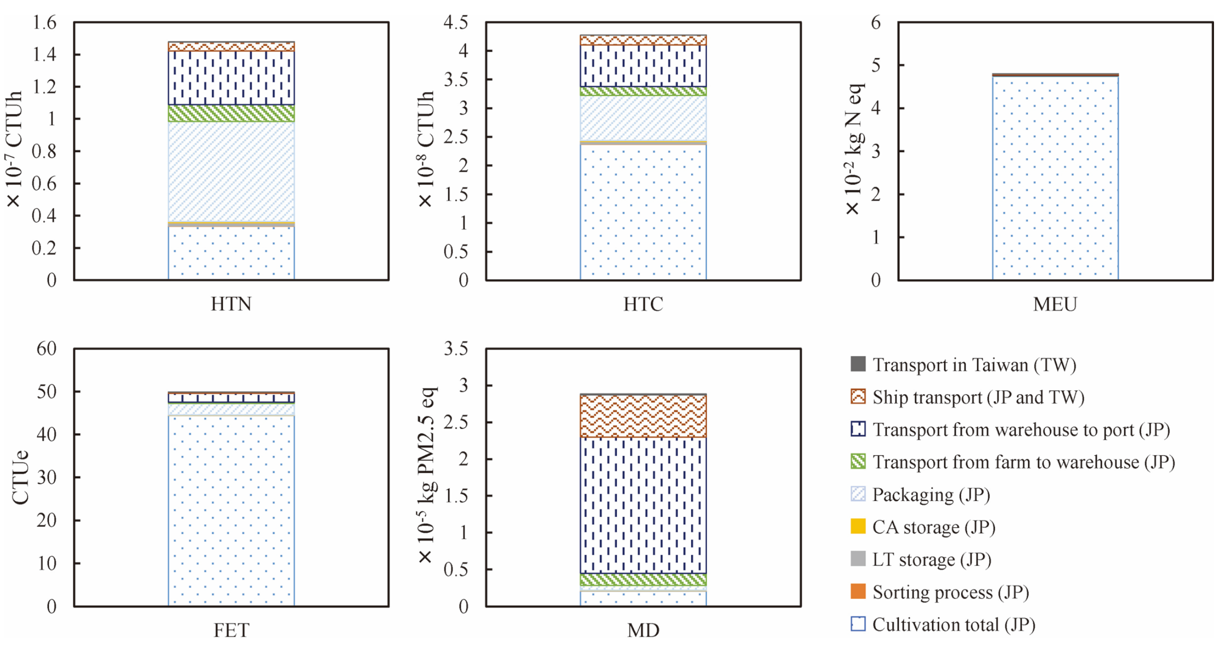
3.3.1. Changing distribution mode from truck to train for Japanese domestic transportation

A modal shift from road to rail may contribute to the construction of a low-carbon transport system. While Fig. 3 (a) shows the base case of transportation modes, Fig. 3 (b) visualizes a new distribution chain, listing the distances and train stations for a proposed modal shift toward using trains with cooling for domestic transport in Japan. Figure 8 (A–B) shows the carbon footprint of the initial scenario using truck transport and the modal shift to using trains for domestic transport in Japan. The impacts of the total apple chain in the base case (truck transportation) and newly proposed case (modal shift to train) were 0.92 kg CO_2 eq and 0.77 kg CO_2 eq, respectively. Thus, the shift toward using train transport reduces the chain impact by 16 %, with the impact of the truck transport stage itself decreasing by 80 %. Yoshikawa et al. (2007) expected an approximately 30 % reduction in the environmental load of transport by introducing a modal shift using trains for fruit distribution in Japan. The obtained ratio in our study (80 %) was larger than the ratio in the previous study by Yoshikawa et al. (2007). This finding shows that introducing a modal shift from truck to train into the apple distribution process



Functional unit = 1 kg apples ready for sale in Taiwan

Fig. 4 Normalized results of the apple exported from Japan to Taiwan



Functional unit = 1 kg apples ready for sale in Taiwan

Fig. 5 Characterized results for each impact category: contributing life cycle stages

Table 5 Percentage of characterized results in each process for the five most relevant impact categories, as well as for the CC impact category

(%)

Processes	CC	HTN	HTC	MEU	FET	MD
Cultivation (JP)	42	23	55	99	89	7
Sorting (JP)	0	0	0	0	0	0
LT storage (JP)	2	1	1	0	0	0
CA storage (JP)	1	0	0	0	0	0
Packaging (JP)	22	42	18	0	5	2
Transport from farm to warehouse (JP)	3	7	4	0	1	6
Transport from warehouse to port (JP)	25	22	17	0	4	64
Ship transport (JP and TW)	6	4	4	1	1	20
Transport in Taiwan (TW)	0	0	0	0	0	0

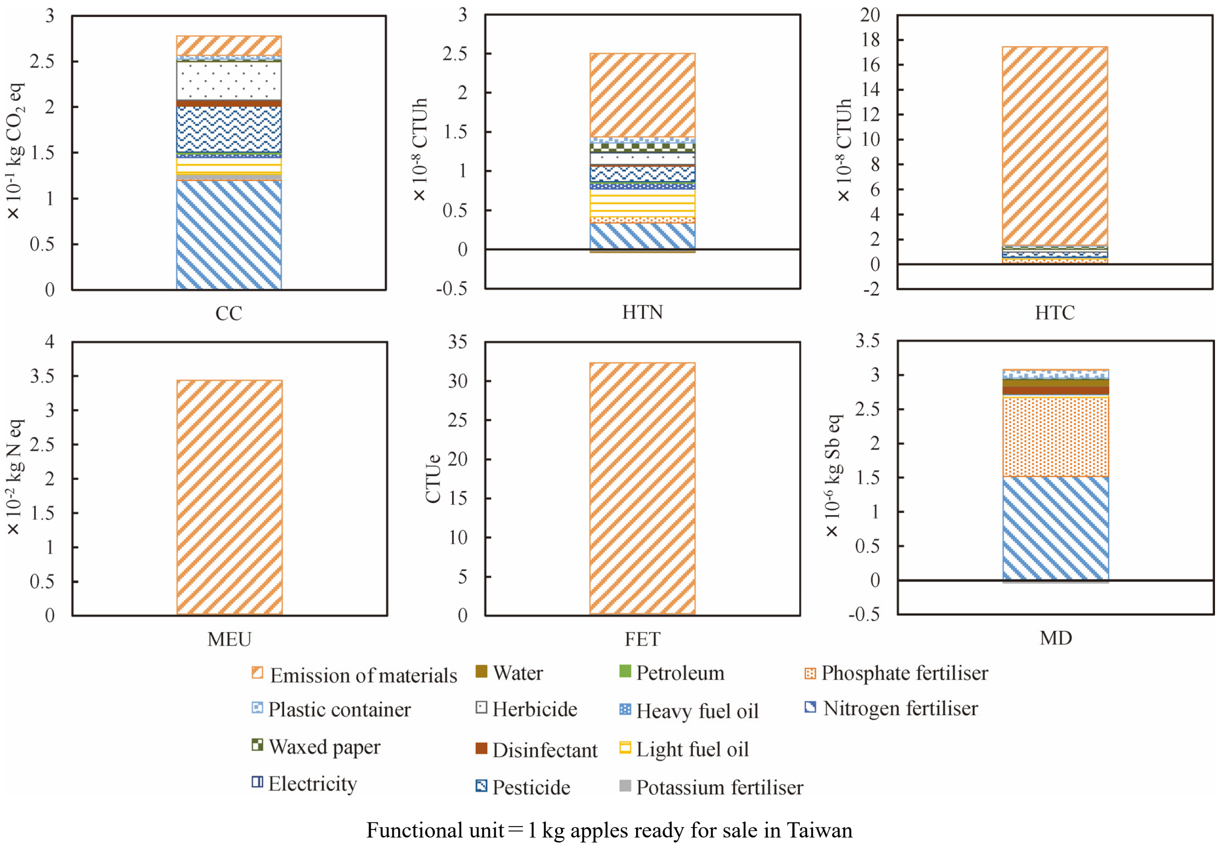
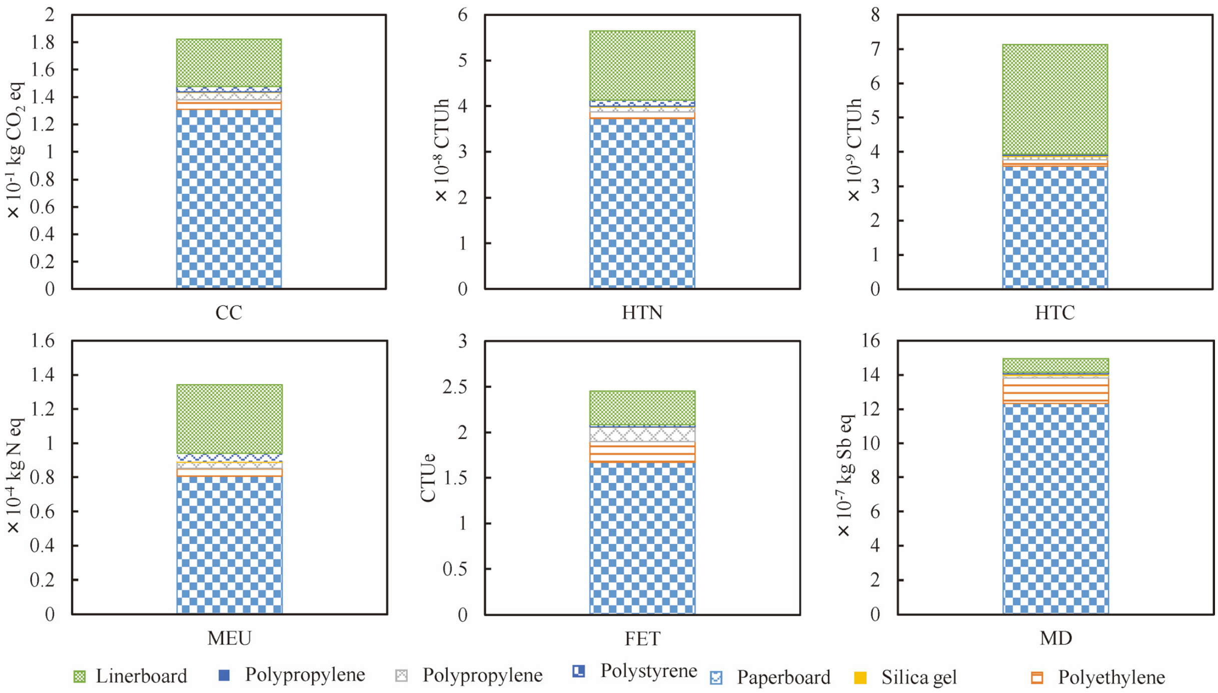


Fig. 6 Characterized results of apple cultivation process for the 5 most relevant impact categories, complemented with the CC impact category

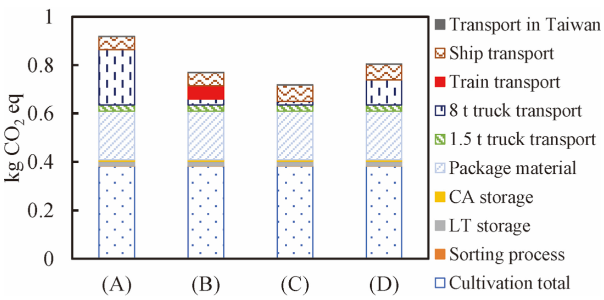
domestically within Japan could contribute to the construction of a more environmentally friendly distribution system.

Fresh fruits and vegetables in Japan are mainly distributed by truck (MAFF, 2017). CO_2 emissions from truck transport account for 87% of the total CO_2 emissions of the transport sector in Japan (MOE, 2016). Therefore, Japan can afford no further delay in implementing plans to abate the environmental burden associated with truck transport. Moreover, truck transport presents increasing transport costs associated with employing truck drivers and the difficulty of establishing a sustainable truck distribution mode in the future in Japan (MLIT, 2016). An overall assessment of the feasibility of making such a modal shift, considering the capacity of the Japanese railway system and the costs associated with rail transport, was, however, out of scope of this paper. We therefore suggest research, businesses and policy makers to look into the possibility of a modal shift in the (apple) distribution process.



Functional unit = 1 kg apples ready for sale in Taiwan

Fig. 7 Characterized results of package materials for the 5 most relevant impact categories, complemented with the CC impact category



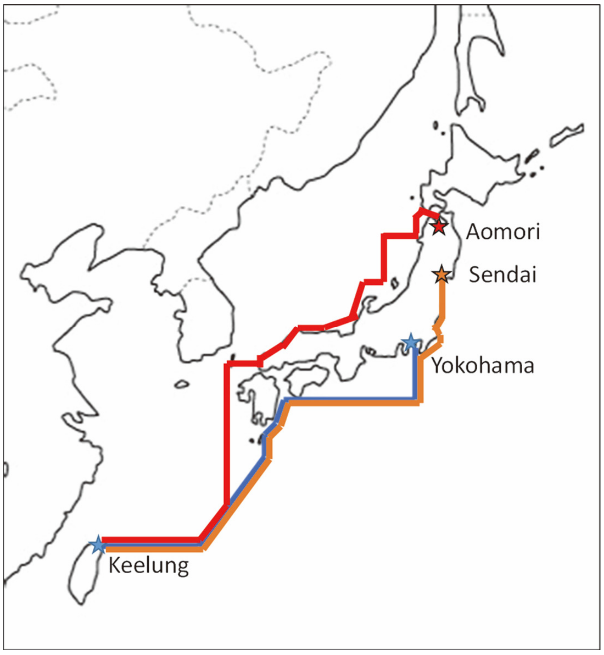
(A) Base case, (B) Modal shift case, (C) Aomori case (minimum distance for load transport), (D) Sendai case (middle case: reduced distance for load transport)
Functional unit = 1 kg apples ready for sale in Taiwan

Fig. 8 Chain optimization, focusing on domestic transportation: Characterized results of CC impact for each scenario

3.3.2. Shortening truck transport by changing to ports closer to farms in the Aomori Prefecture

Another possibility for reducing impacts from domestic truck transport in Japan is reducing the distances traveled by truck. As such, we assessed the possibility of shipping apples from ports closer to the harvesting area, such as Aomori port and Sendai port. Figure 9 shows a map of Japan and Taiwan and lists the different ports under study, with Sendai port representing the greatest logistical hub in the northern region of Japan (one of the eight core international ports in Japan). The associated distribution distances are given in Fig. 3 (C–D).

Figure 8 (C–D) shows the CC impact values for each scenario. Whereas the carbon footprint of ship transport in the Aomori case and Sendai case increased by 22 % and 18 % relative to the base case (Yokohama port), respectively, the impacts of 8 t truck transportation in the Aomori case and Sendai case decreased by 94 % and 55 % relative to the base case (Yokohama), respectively. The carbon footprints of the entire apple chain of the base case, Aomori case, and Sendai case were 0.92 kg CO_2 eq, 0.71 kg CO_2 eq, and 0.80 kg CO_2 eq, respectively. The values of the Aomori case and Sendai case were 78 % and 87 % of the impacts of the base case. These results clearly show that changing the port from Yokohama to Aomori or Sendai could contribute to reducing the environmental burden of fresh apple exports from Japan to Taiwan. To change to a port closer to the harvesting area, the refrigeration facilities around these ports may need to be expanded, a regular shipping route to Keelung from these ports has to be set up (if not yet present), and the phytosanitary system at these ports may need to be strengthened. Ishikawa et al. (2013) reported that injury to fruits and vegetables by vibration in transportation was lower during ship transport than during truck transport in fruit transportation from Japan to Taiwan, Hong Kong, and Thailand. Therefore, food loss by injury in ship transport could be expected to be lower than that in truck transport. Reducing the distances traveled by truck and increasing distances traveled by ship, could thus positively affect food waste during apple distribution. We suggest that future studies look into this, as this could further reduce the carbon footprint of the exported apple.



Map showing the location of the Yokohama port in Japan and Keelung port in Taiwan as used in the initial baseline scenario. Additionally, the two ports Aomori and Sendai in Japan and used for process optimization calculations in this paper, are also shown. The blue, orange and red lines are the sea routes to Keelung port from Yokohama, Sendai and Aomori ports, respectively.

Fig. 9 Location of Aomori, Sendai and Yokohama port in Japan and Keelung port in Taiwan

3.3.3. Comparing the obtained results with other LCA studies of the apple life cycle.

Boschiero et al. (2019) studied greenhouse gas emissions during the post-harvest life of apples as affected by storage type, packaging and transport in northern Italy. The study mentioned that using rail transport or shipping could reduce the environmental costs related to transport by 65−72 % (in comparison with truck transport) if long transportation distances need to be covered, especially when exceeding 300 km of the distance. In the base case of our scenario, the distance by truck transport is 720 km, which is indeed over 300 km. The environmental loads of truck transport in the optimization scenarios in this study (train case, minimum distance for road transport case, and middle case) decreased by 55−94 % relative to the base case, as shown in the previous sections, and the obtained results agree with those reported previously by Boschiero et al. (2019). The transportation efficiency by truck in Japan is not better than that in European countries because smaller trucks such as up to 10 t of load capacity are often in use in Japan, in contrast to the larger scale distribution with 20 t trucks in European countries. This partly explains the decrease in environmental impact when changing the distribution mode from road to rail transport or shipping in Japan, as shown in this research. In addition, shipping from ports closer to farms in the Aomori Prefecture (such as Hachinohe port or Hakodate port) could contribute further to a decrease in the environmental load in apple transportation processes.

In our study, the most relevant process in our apple chain was cultivation, as shown in the previous section (3.2. Carbon footprint hotspots). Previous studies (Cerutti et al., 2013; Goossens et al., 2017; Longo et al., 2017) reported high environmental burdens stemming from the use of fertilizer, pesticide, and fossil fuels in the apple production process. Therefore, the development of apple cultivation processes with low fertilizer, pesticide, and fossil fuel use is more important for reducing the environmental burden of CC impact. Organic cultivation is expected to reduce fertilizer, pesticide, and fossil fuel use. The JAPAN SDGs action platform announced by the Japanese government reported that expanding organic cultivation was one of the highest priority issues to construct a sustainable society (MAFF, 2019). However, the organic cultivation area currently occupies only 0.5 % of the total cultivation area in Japan. Moreover, organic apple cultivation is not promoted because many Japanese growers consider that, in regard to organic cultivation, apple is one of the most difficult agricultural crops (Hanaoka et al., 2014). To spread organic apple cultivation in Japan, national or regional agriculture research organizations should demonstrate possibilities and provide advice on all related technological aspects. A final aspect on this matter is that some previous studies reported that the environmental impact of organic farming per product unit is not necessarily lower than that of conventional farming because lower inputs of fertilizer, pesticide, and fossil fuel in organic farming generally lead to reduced crop yields (Hayashi, 2008; Nemecek et al., 2011; Williams et al., 2006). Optimization of the agricultural stage was, however, beyond the scope of this paper. Hence, future studies on how to maintain a high apple yield (in Japan) under low fertilizer, pesticide, and fossil fuel use are needed.

3.4. Limitations of the current study

Goglio et al. (2015) reported that soil carbon sequestration could potentially offset GHG emissions from fossil fuels by 0.4−1.2 Gt of carbon per year, which is equivalent to 5−15 % of global fossil fuel emissions, therefore, soil carbon sequestration is considered one of the most promising climate change mitigation options for agriculture. Soil carbon sequestration can change as a result of land use changes (Goglio et al., 2015). Therefore, land use changes may play a significant role in the environmental profile of agricultural products (Desjardins et al., 2012; Shrestha et al., 2014). In this study, soil carbon sequestration was not considered due to uncertainties in the environmental impact related to land use changes (Orikasa et al., 2015) and the lack of reliable field data (Borjesson and Tufvesson, 2011). In future studies, a detailed analysis of the environmental impact on the apple production process considering land use changes should be conducted; the protocol has been defined by the IPCC (2019). The uncertainty of the obtained data in the cultivation stage should also be evaluated in future studies.

We select the ILCD 2011 method because we wanted to identify the impact categories to which our analyzed system contributes the most. This is done by normalizing the characterized impact values as described in section 2.4., using the normalization factors provided by EC-JRC (2010). Afterward, for those 5 impact categories with the highest normalized values, we performed a hotspot analysis looking at the contributing life cycle stages and processes. The model based on Japan may be feasible for our study, but at this moment, no such normalization factors for Japan exist. In a future study, a model based on Japan such as the LIME method, could be applied, and the differences between the obtained data by using ILCD and LIME should be discussed.

Approximately 10 % of the food loss and waste of fruits and vegetables occurs during their transportation, a common feature among all countries and regions (FAO, 2011). Therefore, it is important to establish a countermeasure to decrease food loss and waste, and the effect of differences in shock during transportation on the injury rate of fruits and vegetables should be evaluated comprehensively. However, there are few data about the injury rate of fruits and vegetables during transportation in Japan, although some LCA studies have examined the environmental impacts of strawberry and peach transportation during transportation in Japan (Sasaki et al., 2021; 2022a; 2022b; 2023). Construction of a database of injury rates for many kinds of fruits and vegetables in some transportation modes will reveal the effect of the difference in injury rates during transportation of fruits and vegetables on environmental load based on food losses during transportation.

4. Conclusions

We applied a LCA to apples exported from Japan to Taiwan, and the environmental impact of the apple chain was analyzed.

Based on the normalized impact values, the apple chain was found to contribute the most to the HTN, HTC, MEU, FET, and MD impact categories. The cultivation process largely contributed to the MEU and FET impact categories. The packaging process largely contributed to the HTN impact category; the 8 t truck transport process contributed to the MD impact categories; and the ship transport process largely contributed to the MD impact categories.

Based on the post-harvest hotspot within the CC impact category, two optimization options are discussed for reducing the carbon footprint of the apple export chain in terms of transportation mode. Introducing a modal shift (from land to railway transport) in Japanese domestic transportation and changing ship distribution by using a port closer to the farm (and thus reducing inland truck transport) would both result in a lower carbon footprint of the apple chain under study.

The insights obtained from this study provide essential information for the development of a more environmentally friendly apple distribution process from Japan to Taiwan.

Acknowledgments

This work was supported by JSPS KAKENHI JP17K08015, JP22K05901 (Grant-in-Aid for Scientific Research (C)) and JP26850156 (Grant in Aid for Young Scientist (B)), allowing a research stay by Prof. Takahiro Orikasa at KU Leuven as international joint research. The authors thank Prof. Sadao Komori (Iwate University) for providing information about apple cultivation in Japan, Ms. Kasumi Hayakawa (Masters student, Graduate School of Iwate University) for her assistance in collecting inventory data, and Tsugaru Hirosaki Agricultural Cooperative, Japan for their assistance in supplying inventory data on apple postharvest processes.

Conflicts of 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.

Appendix A. Supplementary data

The supplementary data is included with this article.

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(Received: 27 March 2022, Accepted: 28 April 2023)