Heliyon 10 (2024) e32507

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Energy and emissions: Comparing short and long fruit cold chains

Martin du Plessis [a,*], Joubert van Eeden [a], Leila Louise Goedhals-Gerber [b]

[a] *Department of Industrial Engineering, Stellenbosch University, Private Bag X1, Matieland, 7602, South Africa*
[b] *Department of Logistics, Stellenbosch University, South Africa, Private Bag X1, Matieland, 7602, South Africa*

ARTICLE INFO

Keywords:
Cold chain
Carbon footprint
Energy consumption
Seasonal fruit
Sustainable fruit supply chain
Logistics

ABSTRACT

This paper evaluates GHG emissions and energy usage in “short” and “long” cold chains for oranges, table grapes, and apples transported from South Africa to a retail store in Scotland. Novel formulae assess energy usage and emissions based on cold chain duration. “Short” chains show carbon footprints between 0.87 and 1.28 kg CO_2e/kg of saleable fruit, contrasting starkly with extended cold chains. Extending storage durations increases emissions; a one-month extension results in 24–27 % emissions for oranges and grapes and 16 % for apples. Six months of CA storage of apples increases emissions by 96 % compared to “short” cold chains. Energy consumption follows a similar trend as emissions. This research informs policymakers and consumers, emphasising the need for sustainable and “short“ cold chains. This is also the first paper that comprehensively assesses both the energy requirements and emissions outputs in a fruit supply chain based on the combined transport and storage duration of the cold chain from tree to retail markets.

1. Introduction

The global challenge of climate change has become increasingly urgent in recent years due to the undeniable threat of greenhouse gas emissions [1]. In addition, society is also feeling the brunt of high energy prices and the effect of limited energy availability [2]. Fortunately, society is gradually making energy- and environmentally-conscious decisions and is aware of its role in mitigating and reducing the environmental impact of consuming products [3,4]. Retailers, in particular, are stepping up to ensure a transition to sourcing more environmentally sustainable products [5,6].

According to a recent study by Deloitte [4], one of the significant barriers consumers and retailers face in making informed decisions regarding the environmental sustainability of products is access to helpful, accurate information. Surprisingly, almost half of consumers feel they do not have enough information to make informed choices of products when purchasing them [4].

Consumers and retailers should know the energy usage and greenhouse gas (GHG) emissions associated with each product or kilogram of produce they buy. This is particularly true for fresh products such as fruit and vegetables, which can be stored for several months under refrigerated conditions to ensure a year-round supply [3]. Subsequently, the debate about consuming seasonal produce remains a focal point [7,8]. Macdiarmid [9] mentions that several advocates often highlight the potential reduction in carbon footprint as a compelling reason to embrace seasonal eating. Further, the contentious concept of *food miles* [10] has long promoted the prevailing belief that only transportation distance impacts the carbon footprint of fresh fruit.

One element neglected in fresh fruit supply chain studies is how the cold chain length affects energy and emissions [11,12]. This is

* Corresponding author.
E-mail addresses: martinduplessis@sun.ac.za (M. du Plessis), jveeden@sun.ac.za (J. van Eeden), leila@sun.ac.za (L.L. Goedhals-Gerber).

https://doi.org/10.1016/j.heliyon.2024.e32507
Received 21 February 2024; Received in revised form 20 May 2024; Accepted 5 June 2024
Available online 6 June 2024

Table 1
Systematic literature review keywords and synonyms.

		Synonyms for main keywords				
		Cold chain	Energy	Emissions	Fruit	Time
Search engines	**Scopus and EBSCOhost**	“cold chain” OR “refrigeration” OR “cooling” OR “temperature control” OR “chilling”	“energy” OR “fuel” OR “electricity” OR “diesel” OR “petrol” OR “gas”	“emissions” OR “GHG” OR “carbon footprint”	“fruit” OR “vegetable” OR “perishable goods” OR “food”	“time” OR “duration” OR “length” OR “period” OR “season” OR “hemisphere” OR “month” OR “day”
	Google Scholar	“cold chain” OR “refrigeration” OR “cooling” OR “temperature control” OR “chilling”	“energy” OR “fuel” OR “electricity” OR “diesel” OR “gas”	“emissions” “GHG”	“fruit” OR “vegetable” OR “perishables”	“time” OR “duration”

confirmed by several sources, such as [12–15], which iterates the energy and carbon-intensive nature of storing and transporting (i.e. distributing) everyday goods. Temperature-sensitive products, such as fresh fruit, require even more energy to maintain the cold chain, resulting in more emissions [16].

Accurately calculating the energy usage and carbon footprint of moving products in complex global supply chains is, at best, challenging and time-consuming [13,15].

This is particularly difficult for perishable products such as fresh fruit due to the large number of pre-carriage activities undertaken in the country of export, the variation in transport vehicles and equipment used in the country of export, the carbon intensity of energy sources, the duration of refrigerated storage, the variation between different shipments, and the origin-destination pairing, among other considerations. What is certain, however, is that fresh fruit cold chains are particularly energy- and emission-intensive [17].

This paper's objective is to determine the i) emissions and ii) energy usage of "short" and "long" cold chains by examining three fruit (oranges, table grapes, and apples) supply chains from South Africa to a retail supermarket in Edinburgh, Scotland. The primary aim is to assess how the storage duration affects energy use and emissions in these "short" and "long" cold chains. "Short" cold chains (i.e., less than 50 days from tree-to-retail-shelf) represent the current export systems shortest lead times, while "long" cold chains (more than 50 days from tree-to-retail-shelf) are those fruit supply chains where fruit are stored longer than required to ensure a year-round supply to the market. The rationale for the paper is to determine the energy and emissions impact of different cold chain storage durations. The paper also suggests novel formulae for calculating energy usage and emissions based on the duration of the cold chain. This is also the first paper that comprehensively assesses both the energy inputs and emissions outputs in a fruit supply chain based on the duration of the cold chain from tree-to-retail markets, including longterm controlled atmosphere storage as a scenario.

2. Literature review

This section summarises a systematic literature review (SLR) of existing knowledge that assesses fruit cold chain energy usage and emissions. The five-step process proposed by Tranfield and Denyer [18] was used to analyse the literature that reviews, assesses, or

Table 2
Relevant studies assessing the energy consumption and emissions of fruit cold chains.

Study	Commodities assessed	Scope	Geographical region	Energy consumption per functional unit	GHG emissions per functional unit	Assess logistics	Time duration of the cold chain assessed
[21]	Apples	Distribution focussed	Global	Yes	Yes	Yes	No
[22]		Controlled atmosphere storage only	Germany	Yes	No	No	Yes
[23]	Apples and pears	Custom: production, packing, controlled atmosphere storage and cold store storage	South Africa	Yes	Yes	No	No
[12]	Avocados	Custom: packhouse-door-to-port-of-import	South Africa	No	Yes	Yes	Yes
[24]	Bananas	Cradle-to-market	Global	Yes	Yes	Yes	Yes
[11]		Distribution focussed: exporter DC to importer DC	Global	Yes	Yes	Yes	Yes
[25]	Blueberries	Cradle-to-market	USA, Chile	Yes	Yes	Yes	Yes
[26]	Cherries, onions, plums, strawberries, avocados, lemons, celery, oranges, and tomatoes	Cradle-to-grave	USA	No	Yes	Yes	Yes
[27]	Fresh fruit	Cold store facility only	South Africa	Yes	Yes	No	Yes
[17]		Custom: packhouse-door-to-port-of-import	South Africa	Yes	Yes	Yes	Yes
[28]	Fruit and processed products	Cradle-to-grave	Global	Yes	Yes	Yes	Yes
[29]	Fruit and vegetables	Cradle-to-grave	China	Yes	Yes	Yes	No
[30]		Cradle-to-market	Canada	Yes	No	No	Yes
[31]	Strawberries	Cradle-to-grave	Italy	No	Yes	Yes	No
[32]		Custom: transport from farm to packhouse, storage at packhouse, transport to DC, storage at DC, transport to retailer, retailer cold storage	France	Yes	Yes	Yes	No
[33]	Strawberries, lemons, celery, tomatoes, oranges, and avocados	Cradle-to-market	USA	Yes	Yes	Yes	No
[14]	Vegetables, fruit, meat, and aquatic products	Cradle-to-grave	China	No	Yes	Yes	Yes
[34]	Yoghurt, jeans, apples, tomatoes, furniture	Distribution focussed: farm-gate-to-consumer	Global	Yes	Yes	Yes	No

quantifies cold chain energy use and emissions. The steps of the SLR are listed and discussed in the remainder of this section.

Step 1. **Formulate the SLR question**: This literature review asked, "*What literature assesses the energy use and emissions in fruit supply chains based on the cold chain duration?*".

Step 2. **Locating the studies:** Using the keywords and synonyms listed in Table 1, two scientific search engines, EBSCOhost and Scopus, as well as Google Scholar, were used to locate 909 unique studies. The large variation of synonyms for the keywords in Table 1 and the absence of search filters ensured that all relevant literature was found. Note that the synonyms for "fruit" initially included "vegetables" to prevent studies assessing both fruit and vegetables from being omitted.

Step 3. **Select and evaluate all studies:** After exporting all 909 studies to a Microsoft Excel file, the titles and abstracts were manually evaluated to determine their relevance to the SLR. Based on the title and abstract, 862 studies were subsequently eliminated since they were irrelevant to the SLR question in Step 1. The full texts of 43 studies were obtained and assessed in the remainder of the SLR. Four studies could not be obtained.

Step 4. **Analyse and assess studies:** Three of the 43 studies obtained were deemed inappropriate since they were only available in Mandarin. The content of the remaining 40 English studies was then carefully analysed and assessed. This included identifying and coding each study based on the type of *commodities assessed*, the *scope of the study*, the *geographical region*, whether *energy consumption* and *emissions* were assessed on a functional unit level (a product level), if distribution or logistics activities were included in the studies' scope, and finally, if the *time duration of the cold chain was assessed.* This list is also used to report results in Step 5.

Step 5. **Reporting of results**: Nineteen (48 %) of the 40 resources identified in the SLR did not focus on a specific product or commodity. These resources focused on refrigerated trailers, port cold store challenges, cold chain technology, holistic sustainable and resilient cold chains, literature in the field, or other related cold chain or supply chain topics irrelevant to the SLR question.

Further, the studies of [7,19], and [20] were omitted since they focus only on vegetables such as lettuce, tomatoes, cucumbers, onions, etc. – all of which have very different cold chain requirements than fruit.

The contents of the remaining 18 relevant studies that focus on fruit cold chain energy use and emissions are summarised in **Table 2**.

Table 2 shows that the 18 studies assessed a diverse range of commodities. Apples and strawberries were evaluated three times, followed by apples and bananas with two occurrences. Other studies [14,26,28–30,33,34] assess numerous commodity groups – ultimately leading to questionable accuracy of results due to the uniqueness of each commodity cold chain.

In terms of the scope of studies, **Table 2** shows that five (28 %) of the 18 studies had a cradle-to-grave scope, while four (22 %) encompassed a cradle-to-market scope. The remainder of the studies all had different scopes, ultimately limiting their value due to comparability or benchmarking issues.

Regarding energy consumption, 14 (78 %) of the studies in **Table 2** indicated energy consumption, such as electricity, diesel, or other fuel in the cold chain on a functional unit level. This means that 78 % of studies assessed energy usage on a tangible level, such as per kilogram of fruit. In terms of emissions, 16 (88 %) of the studies in **Table 2** assessed GHG emissions of fruit on a functional level, allowing for the calculation of the product's carbon footprint per kilogram of fruit. However, only 12 (66 %) of the studies assessed both energy and emissions.

Despite the large proportion of the cold chain occurring during the logistical process, only 10 (56 %) of the 18 studies evaluate energy, emissions and logistics. Other studies [23,27] assess the energy and emissions of one or more parts of the cold chain, such as storage in cold stores and controlled atmosphere storage.

Finally, of the ten studies identified above that evaluate fruit cold chains' energy consumption, emissions, and the logistics or distribution process, only 5 (50 %) of the ten studies incorporate the duration of the cold chain or time duration of refrigerated storage as a variable. This leads to a significant error in energy and emissions calculations since the latter depends on the cold chain's duration. The remainder of the section will only discuss the five studies that incorporate the duration of the cold chain and energy consumption and emissions.

Svanes [24] assessed the banana supply chain from South America to Norway. This study confirmed the carbon intensity of transport and refrigerated storage, representing nearly 55–70 % of a banana's carbon footprint of 0.78–1.37 kg CO_2e/kg. Svanes's [24] study shows that road transport to the port of export consumed 4.8 ℓ/ton of bananas, while the maritime port operations use 0.59 ℓ diesel/ton and 19.8 kWh/ton. Maritime transport uses 0.36–1.2 ℓ of heavy fuel oil per kilogram of bananas transported.

Fan et al. [11] developed an agent-oriented simulation framework to trade off cost, emission, and quality and applied this to the global banana cold chain – proving the cold chain's significant energy use and emissions. Chapa et al. [25] compared fresh and frozen blueberries using a simulation approach. The study by Chapa et al. [25] showed that fresh and frozen blueberries' carbon footprint and energy consumption were highly sensitive to the length of storage. However, the study by Chapa et al. [25] assumed frozen and fresh blueberry cold chains were limited to two weeks in length. Frankowska et al. [28] assessed the environmental impact of fruits and vegetables consumed in the United Kingdom (UK). They also confirmed that the storage duration can contribute considerably to the impacts of fruits, particularly apples, which can be stored over a long period [28].

Du Plessis [17] developed a methodology to calculate the carbon footprint of fresh fruit distribution. This methodology is similar to the Global Logistics Emissions Council (GLEC) framework developed by the Smart Freight Centre [16]. Although Du Plessis [17] states that the carbon footprint of fresh fruit distribution varies between 0.31 and 0.84 kg CO_2e/kg of fruit, neither the energy consumption nor impact of the cold chain duration is reported adequately.

Except for Svanes [24], no other studies found in the SLR adequately assess the energy use and emissions in fruit supply chains based on the cold chain duration. This confirms the need for further research to establish the nexus between cold chain duration, energy usage and emissions.

3. Methodology

Due to the unique nature of this paper, a custom mixed-methods research methodology was used. The methodology is, however, overall aligned with PAS 2050:2011 (Publicly Available Specification) [35]. PAS 2050 provides a consistent method to quantify a product's life cycle GHG emissions and is built on the principles of *relevance*, *completeness, consistency, accuracy,* and *transparency*. Using the guidance of PAS 2050, the systematic research process and various quantitative and qualitative data summarised in Fig. 1 were used. This ultimately allows for the self-verification of inputs and validation of results. The various steps in the methodology are discussed in the remainder of the section.

3.1. Scoping of project

The first step of the methodology, as shown in Fig. 1, is to define the scope of the assessment. This paper assesses the cold chain of the three fruits, as indicated by the blue-dotted lines in Fig. 2. Fig. 2 also indicates the various transport and storage (i.e. distribution) activities in these fruit supply chains between South Africa and Scotland. The orange and table grape scenarios include all activities after fruit packing in South Africa until the retail store in Scotland. As for apples, Fig. 2 shows that the long-term controlled atmosphere (CA) storage of the apples before packing is also assessed. This scope encompasses the entire cold chains of the various fruits, apart from household storage after purchase.

Household refrigeration is excluded due to its negligible contribution [28] towards the total cold chain energy consumption and emissions and also due to data variability. All GHG emissions are calculated on a well-to-wheel (WTW) or total fuel life cycle basis. Note that refrigerant leakage is excluded from the scope of the assessment. The packaging process and packing material and the building and maintenance of infrastructure and assets are not part of the scope.

3.2. Supply chain scenario for each fruit

Three fruit supply chains originating from South Africa were explicitly chosen since the country is the largest exporter of fresh fruit by volume in the southern hemisphere [36]. The country is, therefore, a well-established global source of fresh produce. South Africa was also the first southern hemisphere country to supply fresh fruit to the United Kingdom (UK) in 1892 [37]. Following these first successful shipments, the UK has become one of the major export markets for South African fresh produce.

The UK remains one of the top three markets for nearly all fruit types exported from South Africa [36]. Subsequently, three fruit types – oranges, table grapes, and apples – were chosen since they are popular and present in nearly every household pantry. These three fruit types represent more than 46 % of the UK fruit consumption, according to Frankowska et al. [28].

Although various potential origin-destination pairs exist, a specific UK retail chain store in Edinburgh was chosen to allow for a comparison of the different fruit types' emissions and energy usage. Subsequently, the three fruit supply chains use specific distribution channels and facilities, such as the DC in Doncaster and the Port of Felixstowe. Therefore, the transport distances and storage durations of the three fruit supply chains have specific values.

Several inputs, such as interviews with subject matter experts (SME), industry data collected from fruit exporters and AgriHub[1] data, observations at logistical facilities, and scenario planning, were used to explore and create different plausible supply chain scenarios. These supply chain scenarios and their variables, such as transport distances and typical storage durations at cold storage facilities, are indicated in Fig. 3.

As stated in Section 1, the following definitions regarding cold chain durations will be used in the remainder of the paper. "Short" cold chains are those fruits that take less than 50 days from the tree-to-retail shelf. Summing the respective durations in Fig. 3 gives a "short" cold chain duration of 41, 51 and 47 days for apples, oranges and table grapes, respectively. These values were then rounded to less than 50 days for fruit not stored long-term for simplicity in the paper. These "short" scenarios represent the minimum lead time without excessive storage in the cold chain. "Long" cold chains (more than 50 days from tree-to-retail-shelf) are those where excessive storage occurs, increasing the duration of the cold chain. "Long" cold chains for table grapes and oranges are up to 80 days or more, while for apples, this can be 180 days or more from the tree-to-retail shelf.

It is important to note that table grapes and oranges are stored under conventional refrigerated conditions in a cold store for one month after being packed – this represents their "long" cold chain. However, apples' storage is distinctly different since they are stored in controlled-atmospheric (CA) conditions for extended periods (6 months in this paper) before packing at a pack house. These storage durations are common or standard practice in the South African fruit export industry and the global fruit supply chain.

Refer to Appendix A for a detailed description of each fruit type's supply chain. Each supply chain described in Appendix A contains important information required for the assessment. It also exhibits the complexity of the distribution process and the detail level assessed in this paper.

[1] AgriHub is an independent legal entity in the South African fruit export sector which collects, stores and provides industry data and statistics.

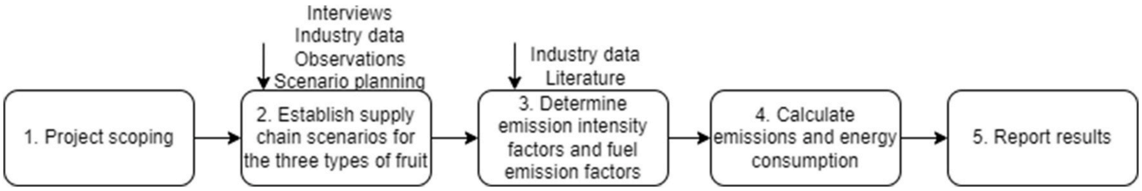

Fig. 1. The research methodology used in this paper.

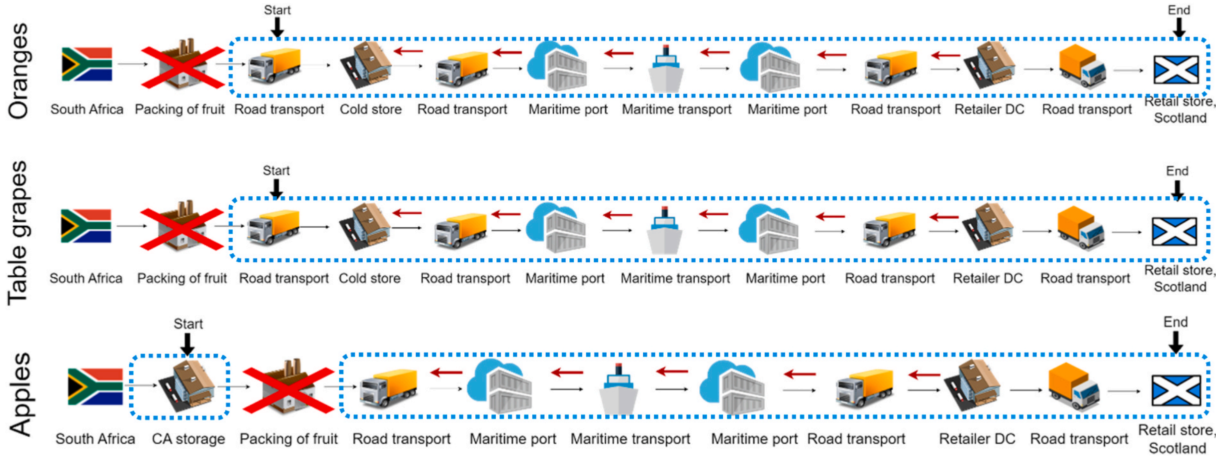

Fig. 2. The scope of the assessment – indicated by the dotted blue lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.3. Determine fuel and emission intensity factors

Determining and using valid and accurate fuel emission factors[2] and emission intensity factors[3] are critical in the assessment. Regarding fuel emission factors, a grid emission factor of 0.97 kg CO_2e/kWh [38] and 0.19 kg CO_2e/kWh [39] was used for South African and UK electricity, respectively. Regarding the WTW emission factors for liquid fuels, a factor of 3.24 kg CO_2e/ℓ was used for diesel, while 3.31 kg CO_2e/ℓ was used for heavy fuel oil. No country-specific values are available to the authors. These fuel emission factors were used to convert emissions (kg CO_2e/kg fruit) to energy consumption (ℓ fuel/kg fruit or kWh/kg fruit).

The emission intensity factors and units of analysis used to quantify emissions are stated in **Table 3**. The emission intensity factors from left to right in **Table 3** indicate the supply chain activities in chronological order as they occur, according to Fig. 3. According to the authors' knowledge, these emission intensity factors are the most relevant and accurate representation of the real-world emissions associated with the proposed supply chain scenarios.

3.4. Calculate emission and fuel consumption

Regarding the methodology used in Step 4, this paper builds on the guidance of Du Plessis's [17] doctoral thesis, which focused on assessing the emissions of the South African fruit export industry logistics. The peer-reviewed work of Du Plessis [17] developed a comprehensive carbon mapping framework and emission intensity factors for the fruit industry to determine the total emissions of a shipment (t CO_2e) and the carbon footprint (kg CO_2e/kg fruit) due to the distribution of fruit. In addition to Du Plessis [17], the Global Logistics Emissions Council (GLEC) Framework [16] was also used to inform methodology and emissions factors.

This paper calculates each activity's carbon footprint (kg CO_2e/kg fruit) according to Du Plessis [17]. To calculate the carbon footprint of all activities in the supply chain, Equation (1) was used:

$$Carbon\ Footprint_{Total} = \frac{\sum \frac{Emission\ Intensity\ Factor_i \times Logistical\ Data_i}{Nett\ Weight\ of\ Fruit_i}}{(1 - Losses\ - Wastage\ )} \tag{1}$$

[2] A fuel emission factor is a numerical value that represents the amount of greenhouse gas emissions (CO_2e) released into the atmosphere per unit of fuel consumed.

[3] In this paper, an emission intensity factor is a numerical value which indicates the average amount of greenhouse gas emission (CO_2e) emitted when performing a supply chain activity.

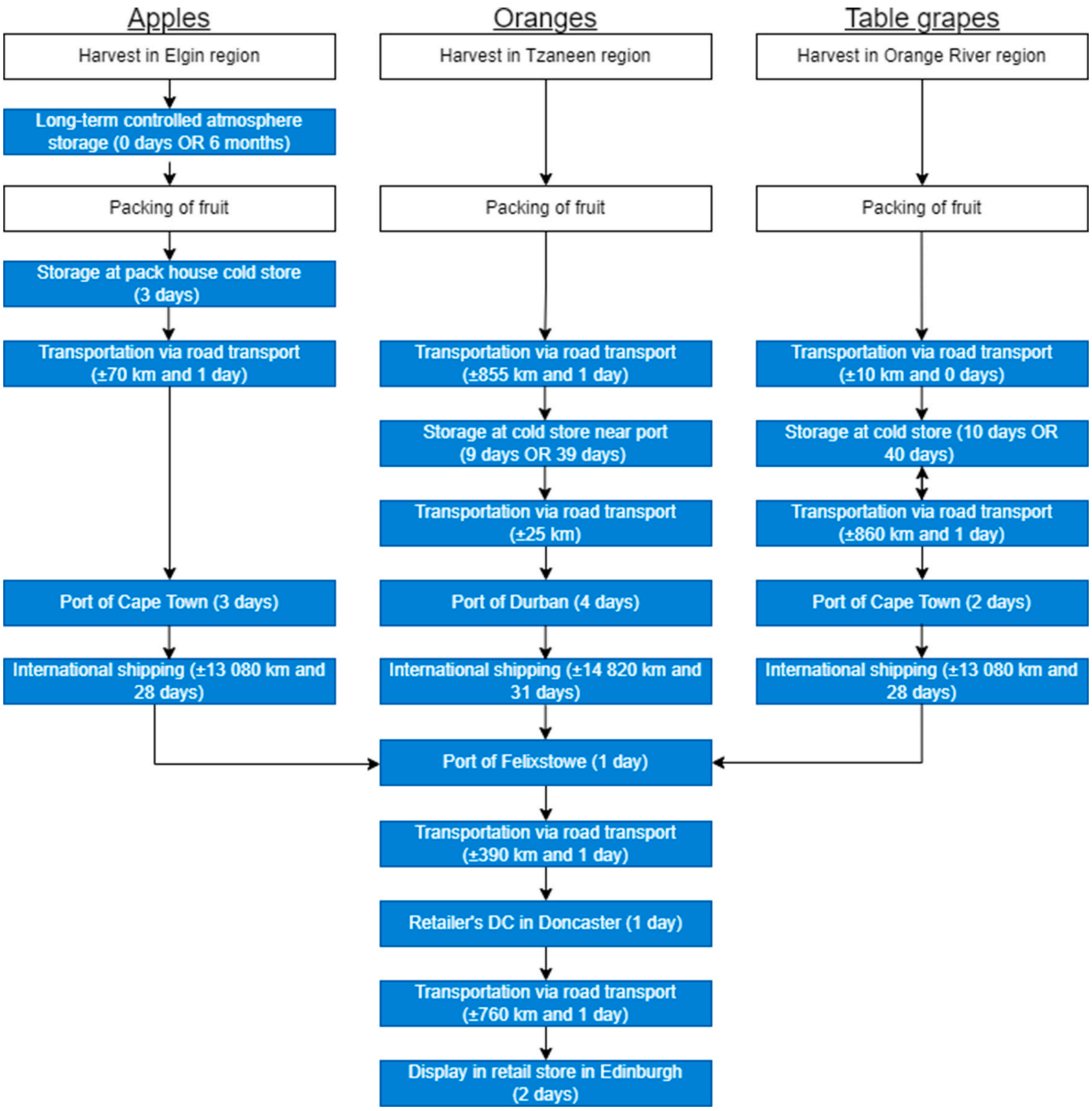

Fig. 3. The supply chain scenario of each fruit type, with the cold chain indicated by the blue sections. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Where: *Carbon Footprint*$_{Total}$ is the amount of CO_2e emissions (kg) emitted per kilogram (kg) of sold fruit, *Emission Intensity Factor*$_i$ is the emission intensity factor from **Table 3** for activity *i, Logistical Data*$_i$ are variables specific to activity *i* such as weight, distance, storage duration, the load factor of vehicle, percentage empty running, and the repositioning of a container. *Nett Weight of Fruit*$_i$ is the nett weight of fruit (kg) involved in activity *i*, *Losses* are the percentage (%) of fruit spoilt during the distribution process up to retail shelf, and *Wastage* is the percentage (%) of fruit fit for human consumption not sold. This paper uses 4 % and 5 % loss and wastage percentages, according to the FAO [42].

To calculate the energy consumption (ℓ fuel/kg fruit or kWh/kg fruit) of the supply chains, the carbon footprint results from Equation (1) are grouped according to the type of fuel used in the logistical activity (i.e. electricity for logistical facilities, diesel for road transport and other mobile equipment, and heavy fuel oil for the maritime section) and divided by the fuel emission factors mentioned in Section 3.3. Energy consumption is, therefore, derived from emissions.

Refer to the Microsoft Excel file titled *Energy and Emissions Calculations* to view detailed data and calculations for each of the three fruits. The results of the three scenarios are reported next.

Table 3
Emission intensity factors used to quantify emissions.

	Pre-carriage					Main carriage	Post-carriage				Retail
	Controlled-atmosphere storage (kg CO_2e t-day^{-1})	Road transport (g CO_2e/t-km)	Cold store (kg CO_2e pallet-day^{-1})	Road transport (g CO_2e/t-km)	Maritime container terminal (kg CO_2e/container, kg CO_2e day^{-1})	Container vessel (g CO_2e/TEU-km)	Maritime container terminal (kg CO_2e/container, kg CO_2e day^{-1})	Road transport (g CO_2e/t-km)	Storage and transhipment in DC (kg CO_2e/t)	Road transport (g CO_2e/t-km)	Retail display (kg CO_2e/m^2 year)
Oranges	–	67	7.52	112	60.2, 175	276.2	60.2, 34.8	111.2	12.3	253.8	193.4
Table grapes	–	107	7.52	115							
Apples	2.97	115	7.52	–							

Source: [17,39–41]

4. Results and discussion

The results are discussed across four sections. Section 4.1 assesses the carbon footprint of each fruit for the current export system's "short" cold chain duration. Section 4.1 also evaluates the emissions contribution of activities in each fruit supply chain to identify *hot spots* in the distribution process. Section 4.2 investigates the impact of increases in the storage duration in each fruit supply chain to establish the emissions impact of a "longer" cold chain. Section 4.3 discusses the energy consumption of the three fruit supply chains. Finally, Section 4.4 provides novel formulae to calculate the expected emissions and energy usage of each cold chain based on the duration of storage.

4.1. Carbon footprint of short fruit supply chains

The carbon footprint (kg CO_2e/kg of fruit) of the orange, table grape, and apple supply chains is shown in Fig. 4. The emission results in Fig. 4 reflect each fruit's typical "shortest" cold chain duration – meaning no excessive fruit storage occurred in the supply chain. The carbon footprint values, therefore, represent the typical average emissions of fruit when it lands on the retail shelf. According to Fig. 4, the carbon footprint for oranges is 0.87 kg CO_2e/kg of fruit, 1.28 kg CO_2e/kg of table grapes, and 0.88 kg CO_2e/kg of apples.

Fig. 4 shows that maritime transport contributes 41–53 % of these "short" cold chain's emissions while road transport contributes 30%–37 %. This confirms the extent of the emissions contribution and the need to decarbonise these two activities in fruit distribution.

Although not very significant, the contribution of other activities is still notable. Cold stores and the DC, maritime ports, and retail store in Edinburg collectively contribute approximately 12 % to the total carbon footprint of the "short" cold chains. Further, the impact of food losses during distribution and retail wastage is evident in Fig. 4, which increases the carbon footprint of saleable fruit by

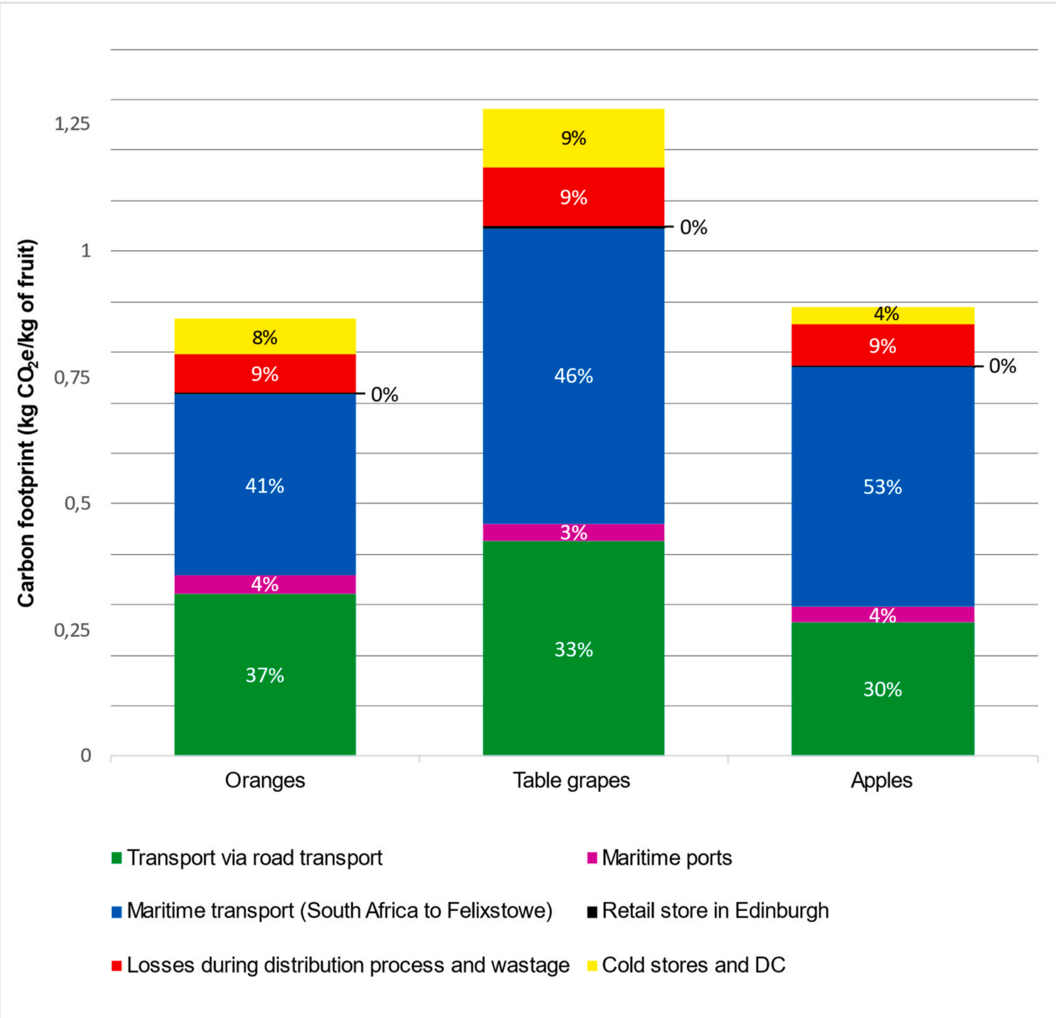

Fig. 4. The carbon footprint comparison of the three fruit supply chains.

a further 9 %.

Fig. 4 also shows a noticeable difference between the carbon footprints of oranges/apples and table grapes – even though all three fruits have a "short" cold chain. This difference between oranges/apples and table grapes is primarily due to the grapes being a "lightweight" fruit commodity. One high-cube pallet of table grapes weighs 30.6 % less than a similar pallet of oranges or apples. This results in each kilogram of grapes being responsible for "more" emissions.

A detailed overview of each emission-generating activity between the packhouse and the retail shelf is also required to identify the proportional contribution of pre-, main-, and post-carriage activities. Fig. 5 indicates the proportional contribution to the total carbon footprint of the table grapes.

Fig. 5 shows that pre- and post-carriage activities, losses, and wastage in the specific table grape supply chain contributed 54 % to the total carbon footprint. The maritime leg, however, remains the single most significant emissions contributor (46 % of total emissions) to the carbon footprint of the grapes. As for road transport, the last-mile road transport between the retailer's DC and retail store in the UK is responsible for 19 % of the total product carbon footprint, while the pre-carriage road transport in South Africa contributed 10 % to the emissions. Further, the contribution of the retail phase is negligible compared to other cold chain activities since it represents 0.35 % of the total emissions in Fig. 5.

Further, there is also a remarkable similarity between all three fruits' supply chains regarding cold chain emissions and transport-related emissions. In all three fruit supply chains, the proportional contribution of refrigeration is between 28 and 30 % of emissions, while the remaining 70–72 % is due to the physical transport of the fruit.

4.2. *The impact of extending the cold chain duration*

Before assessing the emissions impact of storing fruit for extended periods, it is important to note that apples are stored differently than oranges and table grapes. As discussed in Section 3.2, table grapes and oranges are stored under conventional refrigerated conditions in a cold store for one month after being packed. However, apples' storage is distinctly different since they are stored in controlled-atmospheric (CA) conditions for extended periods (6 months in this paper) before packing at a pack house.

The impact of extending the fruits' cold chain length or duration of refrigerated storage is shown in Fig. 6[4]. Storing oranges in a commercial South African cold store for one month (30 days) longer increases the emissions of the fruit by nearly 24 % (206 g CO_2e/kg of oranges), resulting in a carbon footprint of 1.07 kg CO_2e/kg of saleable oranges. Similarly, storing table grapes for one month longer results in a 27 % (344 g CO_2e/kg of fruit) increase in emissions to 1.63 kg CO_2e/kg of grapes. Fig. 6 shows that extending these fruits' cold chain by one additional day increases the carbon footprint of the fruit by nearly 1 %.

As for apples, Fig. 6 shows that extending the duration of controlled atmosphere storage by one month leads to a 16 % (144 g CO_2e/kg of fruit) increase in the carbon footprint to 1.03 kg CO_2e/kg of apples. It is evident from Fig. 6 that a 30-day elongation in the cold chain length of apples is not as carbon-intensive as is the case with oranges or table grapes. This is due to the difference in the fruit's cooling methods and the typical source of electricity used.

However, when extending the duration of storage for apples to six months (180 days), it is evident that the emissions increase substantially. Fig. 6 shows that increasing the cold chain by six months leads to an emissions increase of 96 % (850 g CO_2e/kg of apples) to 1.73 kg CO_2e/kg of fruit. Although a storage period of six months in a controlled atmosphere may seem excessive, it is common practice in the pome fruit industry to ensure a year-round supply of apples on the global market. A six-month storage period is the theoretical upper limit for Southern Hemisphere fruit to the UK since Northern Hemisphere fruit would be available beyond that. However, longer periods of CA storage are common. This iterates the potential impact that long-term cold storage activities can have on the emission intensity of perishable products.

This section shows that storing fruit such as oranges, table grapes and apples for extended periods, maintaining the cold chain, and transporting the fruit between a packing facility in South Africa and a retail store in Edinburgh emits close to or more GHG emissions than the weight of the fruit distributed. This iterates the emissions impact of storing fruit for long durations compared to other distribution activities.

4.3. *Energy consumption of short- and long-fruit supply chains*

Results show that apart from electricity usage, there is a remarkable similarity between diesel and heavy fuel oil consumption in "short" and "long" cold chains. This is because "long" cold chains use stationary facilities in the supply chain (cold stores and controlled atmosphere storage at packhouses) to extend the cold chain duration instead of mobile transport equipment, which uses diesel or heavy fuel oil as an energy source. According to **Table 4,** diesel and heavy fuel oil usage in all fruit cold chains varies between 0.08 and 0.13 ℓ of diesel/kg fruit and 0.11–0.18 ℓ of heavy fuel oil/kg fruit, respectively.

However, the difference between "short" and "long" cold chains (additional 30 days of storage) increases electricity usage in the cold chain by 126–146 %. Increasing the storage duration of apples by six months (180 days) in controlled atmospheric conditions in South Africa leads to an electricity consumption increase of 727 % compared to the "short" apple cold chains in Section 4.1. This iterates the energy-intensive nature of maintaining the cold chain requirements – especially for extended periods.

Apart from the difference between "short" and "long" cold chains, there is also a significant difference between the energy

[4] Note that the emissions due to losses and wastage increase proportionally, although they remain 9 % of the overall emissions.

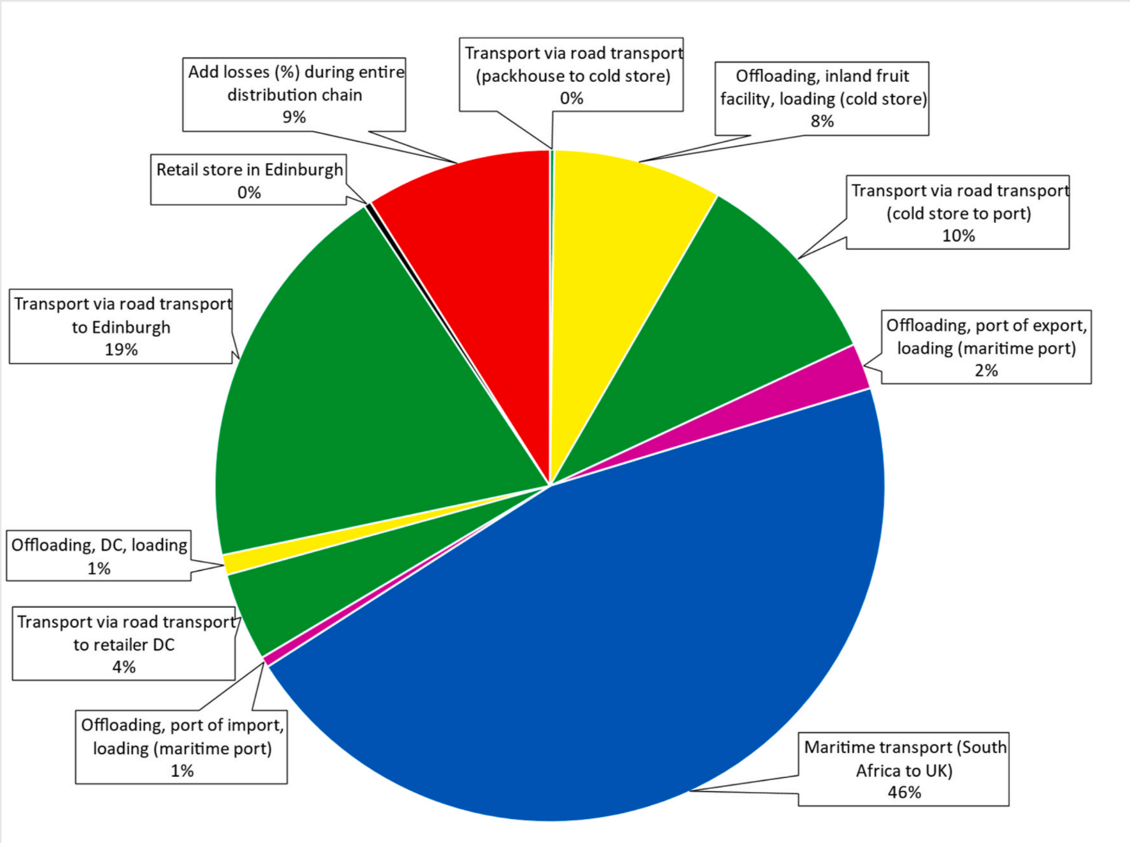

Fig. 5. Overview of the carbon footprint of table grapes from a packhouse in South Africa to a retail shelf in Edinburgh.

consumption of each fruit type. The differences between fruits with the same cold chain length in Table 4 are due to fruit characteristics such as weight, volume, and energy-intensive nature of storage.

4.4. Formulas to calculate emissions and energy usage

This section provides novel formulae to determine fruit supply chains' emissions and energy usage based on the cold chain duration. Equation (2) and the corresponding coefficients in Table 5 can be used to determine the fruit's carbon footprint based on the storage duration.

$$Carbon\ Footprint_{Fruit} = A \times Days + B \tag{2}$$

Where: $Carbon\ Footprint_{Fruit}$ is the amount of CO_2e emissions (kg) emitted per kilogram (kg) of sold fruit in a retail store, A is the coefficient representing the emissions emitted (kg CO_2e/kg-day) when storing the fruit for one additional day, *Days* are the number of additional days the fruit is stored, and B is the coefficient indicating the minimum carbon footprint (kg CO_2e/kg fruit) of the cold chain scenario.

As for energy consumption, Equation (3) and the recommended coefficients in Table 6 can be used to determine the electricity consumption in each fruit cold chain. The diesel and heavy fuel oil consumption values are found in Table 4 in Section 4.3 and, therefore, are not repeated.

$$Electricity_{Fruit} = C \times Days + E \tag{3}$$

where: $Electricity_{Fruit}$ is the amount of electricity (kWh) consumed per kilogram (kg) of sold fruit in a retail store, C is the coefficient representing the electricity consumption (kWh/kg-day) when storing the fruit for one additional day, *Days* are the number of additional days the fruit is stored, and E is the coefficient indicating the minimum electricity consumption (kWh/kg fruit) of the cold chain scenario. Note that the *Days* duration for fruit exported from the Southern Hemisphere to the Northern Hemisphere is typically not more than 180 days. In contrast, for local produce sold in the Southern Hemisphere, 300 days is typical.

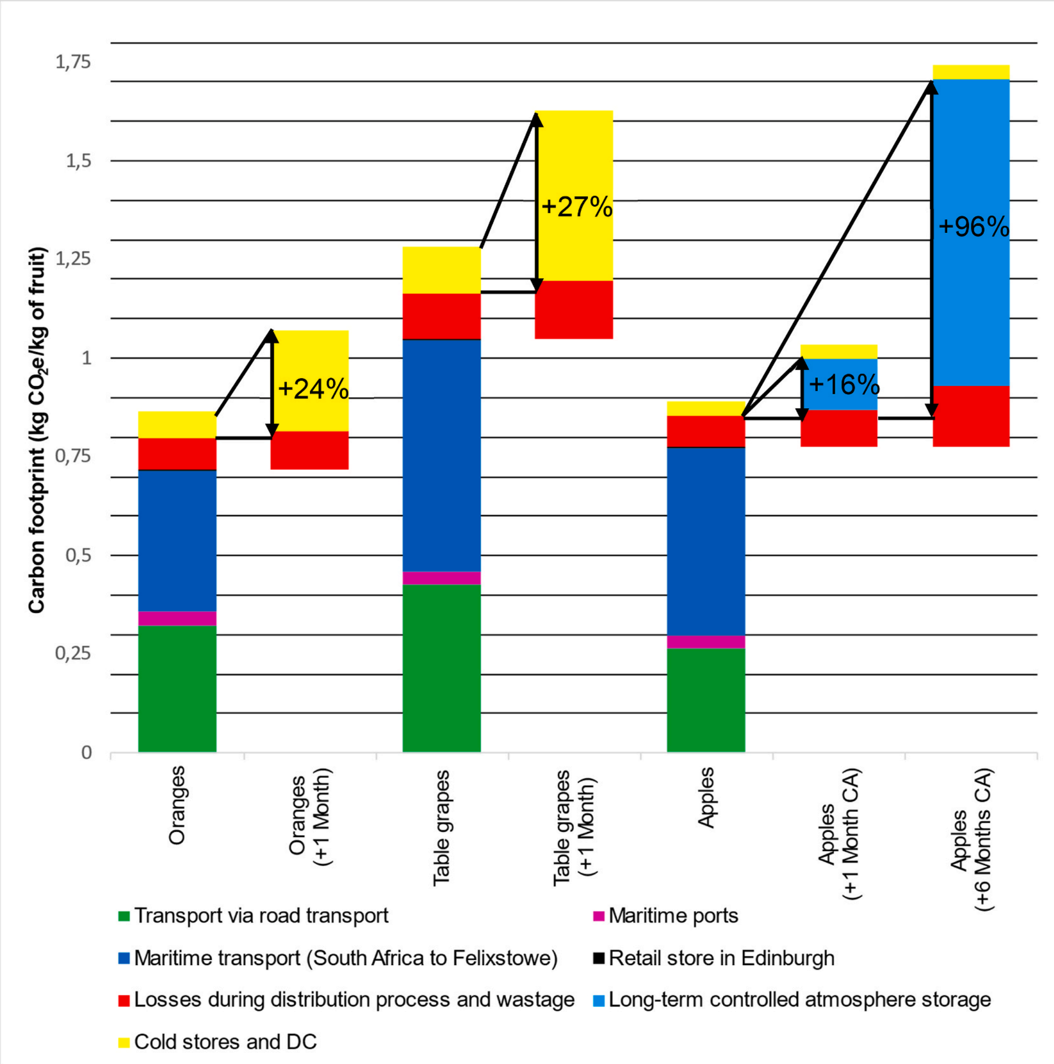

Fig. 6. The emissions impact of increasing the cold chain length.

Table 4
The energy consumption of the different fruit.

	Diesel (ℓ/kg fruit)	Heavy fuel oil (ℓ/kg fruit)	Electricity (kWh/kg fruit)
Short cold chains			
Oranges	0.10	0.11	0.15
Table grapes	0.13	0.18	0.22
Apples	0.08	0.14	0.11
Long cold chains			
Oranges (+1 Month)	0.10	0.11	0.34
Table grapes (+1 Month)	0.13	0.18	0.54
Apples (+1 Month CA)	0.08	0.14	0.25
Apples (+6 Months CA)	0.08	0.14	0.91

5. Conclusion

This paper assessed the i) GHG emissions per kilogram of fruit and ii) energy usage of “short” and “long” cold chains by examining three fruit (oranges, table grapes, and apples) supply chains from South Africa to a retail supermarket in Edinburgh, Scotland. The primary aim was to assess how the storage duration influences energy use and emissions in these fruit cold chains. In addition, the paper also developed novel formulae for calculating energy usage and emissions based on the duration of the cold chain. From the

Table 5
Coefficients A, B, and Days interval used in Equation 2.

	A (kg CO_2e/kg-day)	B (kg CO_2e/kg fruit)	Days (min to max)
Oranges	0.0069	0.865	0–90
Table grapes	0.0115	1.282	0–90
Apples	0.0046	0.889	0–300

Table 6
Coefficients C, E, and Days interval used in Equation 3.

	C (kWh/kg-day)	E (kWh/kg fruit)	Days (min to max)
Oranges	0.0063	0.15	0–90
Table grapes	0.0107	0.22	0–90
Apples	0.0044	0.11	0–300

literature section, it is clear that this is the first comprehensive paper that assesses both the energy and emissions in a fruit supply chain based on the duration of the cold chain from tree to retail markets.

The results highlight the significant variation in different fruit supply chains' energy use and GHG emissions due to different cold chain durations, transport distances, product characteristics and other distribution-related circumstances.

The carbon footprint of "short" cold chains (fruit such as oranges, table grapes, or apples not refrigerated for extended periods, i.e. less than 50 days from tree-to-retail-shelf) varies between 0.87 and 1.28 kg CO_2e/kg of saleable fruit. Extending the cold chain length or duration of refrigerated storage to "long" substantially impacts emissions. Increasing the cold chain duration by one month increases orange and table grape emissions by approximately 24 % and 27 %, respectively, while a similar extension for apples in controlled atmosphere (CA) storage results in a 16 % emissions increase. This fundamental difference is where and how storage occurs, ultimately resulting in different carbon intensities of the fruit. However, apples stored for six months see a 96 % emissions surge, reaching 1.73 kg CO_2e/kg of apples. This underscores the considerable impact of extending the duration of refrigerated storage on emissions, particularly in ensuring year-round fruit supply and emphasising the need for more sustainable cold chain practices.

Similarly to the emissions, the energy consumption (diesel, heavy fuel oil, and electricity) varies considerably for the different fruit types. The energy consumption for "short" cold chains varies between 0.08 and 0.13 ℓ of diesel/kg fruit, 0.11–0.18 ℓ of heavy fuel oil/kg fruit, and 0.11–0.22 kWh of electricity/kg of fruit. Although "long" cold chains use a similar amount of diesel and heavy fuel oil due to similar distribution conditions, they use significantly more electricity. Increasing the cold chain by 30 days results in a 126–146 % increase in electricity usage. As for apples, increasing the CA storage duration by six months increases electricity consumption by 727 % compared to the "short" apple cold chain.

The study also identified the emission-intensiveness of distribution activities in the supply chain. Mobility activities are the most difficult to decarbonise or abate due to their dependence on fossil fuels [13]. Maritime transport contributes 41–53 % of the emissions, while road transport represents 30%–37 % of the total distributional emissions. The remainder of distribution activities, such as the cold stores, the DC, maritime ports, and the retail store in Edinburg, collectively contribute 12 % to the total carbon footprint of the "short" cold chains. These stationary activities are easier to decarbonise due to the possibility of installing and using renewable energy sources such as rooftop photovoltaic (PV) solar as a source of energy. However, the net impact of decarbonising stationary activities is limited. Significant effort is required to decarbonise maritime and road transport to reduce the total carbon footprint of these products.

This study contributes to the body of knowledge on sustainable food systems. It provides important information for policymakers, researchers, and consumers to make informed decisions about the environmental impact of their food choices. Overall, this research underscores the importance of reducing energy consumption and emissions associated with fruit supply chains to achieve a more sustainable food system.

Research funding

This research was partially funded by the Royal Academy of Engineering, UK: TSP2021 100 310. The funders of this research played no role in the contents of this paper.

Data availability statement

The data used in this study has not been published. It is, however, included as a supplementary Microsoft Excel file titled *Energy and Emissions Calculations*.

CRediT authorship contribution statement

Martin du Plessis: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Joubert van Eeden:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition. **Leila Louise Goedhals-Gerber:** Writing – review & editing, Supervision, Resources, Project administration.

Declaration of competing interest

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

Appendix A

This appendix describes the supply chain scenario of the three fruits assessed in the paper.

Oranges

The scenario for oranges pertains to Valencia oranges being exported via the Port of Durban in South Africa to a retailer in Edinburgh, with the Port of Felixstowe as a discharge point. The distribution process utilises refrigerated and ambient road transport and refrigerated deep-sea ocean transport by reefer container.

Oranges are harvested in the Letsitele region in the Limpopo province in South Africa and packed into 15 kg (nett weight) telescopic cartons. High-cube pallets with a gross weight of 1308 kg are built by packing 80 boxes of oranges onto a pallet. Since citrus is harvested during the colder winter months and oranges are not prone to quick spoilage, the fruit is transported by interlink tautliner (curtain side) truck under ambient conditions. The truck is loaded with twenty-six pallets, resulting in a payload of 34 008 tonnes. The truck then travels 855 km via the R36, N11 and N3 routes to a cold store located in the Port of Durban. The pallets are offloaded from the truck and, after being inspected, stored at a temperature of 2 °C. In addition, a minimum ventilation of 15 cubic meters per hour and relative humidity of 95 % is maintained.

From this point onwards, the refrigeration requirements must be maintained throughout the cold chain. The fruit is stored for nine OR 39 days in the cold store, where 20 of the high-cube pallets are loaded into an integral reefer container. Since the cold store is only 25 km from the port of export, a genset to power the reefer is not required. A tri-axle truck tractor with a semi-trailer then transports the container from the cold store to the reefer stack in the port. Once offloaded, the reefer is stored in the reefer terminals reefer stack for four days, whereafter it is loaded into a container vessel. The vessel then travels 8001 nautical miles (14 819 km) via several ports to the point of discharge in the Port of Felixstowe. This deep-sea voyage will take approximately 28 days from the Port of Durban to the Port of Felixstowe.

Upon arrival in the Port of Felixstowe, the reefer container is offloaded from the container vessel and stored in the reefer stack in the container terminal for one day. The integral reefer container is loaded onto an articulated truck and connected to the trailer's genset to maintain the cold chain. The truck combination then travels 390 km to the food retailer's DC in Doncaster, where the fruit is stored for one day. In this DC, several different products are combined to create a single shipment for a retail shop in Edinburgh. A rigid refrigerated truck then transports one pallet of oranges and other food products 760 km to the retail store in Edinburgh. Upon arrival, the oranges are offloaded and packed on a retail shelf in the shop. On average, the fruit is sold after two days of display in the retail shop.

For this specific scenario, it is deemed that the reefer container is repositioned empty back to South Africa while the interlink tautliner truck loads a return load in the Port of Durban before returning to the vicinity of Letsitele, resulting in an average empty running of 10 %. The rigid refrigerated truck and container truck involved in the post-carriage in the UK also returned empty to the DC and Port of Felixstowe, respectively.

Table Grapes

Red seedless table grapes are produced in the Orange River region in South Africa and exported to a retailer in Edinburgh via the Port of Felixstowe by road and deep-sea transport.

Once ripe, the grapes are harvested and packed into 4.5 kg cartons (nett weight of fruit) at a packing facility. High-cube pallets weighing 908 kg (gross weight) are built by packing 160 boxes of grapes on a pallet. The pallets are then transported to a cold store located 10 km away from the packing facility in Kakamas. Since the cold store is nearby, a double-axle rigid flatbed truck is used to transport eight pallets at a time. The load is covered with tarpaulins (sails) to protect the fruit during the short trip. Once the truck arrives at the cold store, the fruit is offloaded from the truck and moved into the cold store. The grapes are stored at an optimal temperature of minus 0.5 °C and 90–95 % relative humidity throughout the cold chain process. No controlled atmosphere is required since grapes do not ripen further after harvest (non-climatic). The empty truck returns to the packing facility to collect and deliver three loads per day. All grapes are stored in the facility for ten OR 40 days until further shipping commences.

Twenty pallets of fruit are loaded into a 40-foot-high-cube integral reefer container carried by an articulated truck with a skeletal trailer. The trailer is equipped with a genset to power the reefer during transport. The reefer-container-truck combination then travels 860 km in 12 h to the Port of Cape Town via the N14 and N7 routes, where the container is offloaded and stored in the reefer terminal's reefer stack for two days. The reefer is then drawn from the reefer container stack and loaded onto a container vessel. The vessel then travels 13 080 km to the Port of Felixstowe in 16 days.

Upon arrival in the Port of Felixstowe, the reefer container is offloaded from the container vessel and stored in the reefer stack in the container terminal for one day. The integral reefer container is loaded onto an articulated truck and connected to the trailer's genset to maintain the cold chain. The truck combination then travels 390 km to the food retailer's DC in Doncaster, where the fruit is stored for one day. In this DC, several different products are combined to create a single shipment for a retail shop in Edinburgh. A rigid refrigerated truck then transports one pallet of oranges and other food products 760 km to the retail store in Edinburgh. Upon arrival, the oranges are offloaded and packed on a retail shelf in the shop. On average, the fruit is sold after two days of display in the retail shop.

The reefer container and all trucks were repositioned empty to the point of loading through the same distribution activities as was the case in the forward distribution chain.

Apples

In the Elgin region in the Western Cape, Royal Gala apples are harvested and stored for one month OR six months in large bins in a controlled atmosphere (CA) environment until packing begins. Alternatively, the fruit is packed immediately. The apples are destined for a retailer in Edinburgh.

Bins of apples are removed from the controlled atmosphere storage rooms and packed into 18.25 kg cartons (nett weight). Fifty-six cartons are then packed onto a pallet to create a high-cube pallet weighing 1106 kg (gross weight). A 40-foot-high-cube integral reefer container, transported by an articulated truck, is loaded with twenty pallets. The truck's trailer has an underslug genset to power the reefer container during the 2-h road journey between the packing facility in Grabouw and the Port of Cape Town. After the 70 km journey, the reefer container is offloaded and stored for three days in the container terminal's reefer stack, where the reefer unit is plugged in. The container is then drawn and loaded onto a container vessel (Post-Panamax vessel) and travels 7061 nautical miles in 18 days to the Port of Felixstowe, United Kingdom (UK).

The vessel makes several port calls en route to the UK. An optimal temperature of minus 0.5 °C and relative humidity of 95 % is maintained throughout the distribution process. After arrival at the Port of Felixstowe, the reefer container is offloaded and distributed to retailers. The integral reefer container is loaded onto an articulated truck and connected to the trailer's genset to maintain the cold chain. The truck combination then travels 390 km to the food retailer's DC in Doncaster, where the fruit is stored for one day. In this DC, several different products are combined to create a single shipment for a retail shop in Edinburgh. A rigid refrigerated truck then transports one pallet of oranges and other food products 760 km to the retail store in Edinburgh. Upon arrival, the oranges are offloaded and packed on a retail shelf in the shop. The fruit is sold on average after two days of display in the retail shop. The reefer container and all trucks were repositioned empty to the point of loading through the same distribution activities as was the case in the forward distribution chain.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e32507.

References

[1] IPCC, Summary for policymakers, in: H.-O. Pörtner, D. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (Eds.), Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022, pp. 3–33.

[2] IEA, What Is behind Soaring Energy Prices and what Happens Next?, Paris, 2021.

[3] D.B. Grant, A. Trautrims, C.Y. Wong, Sustainable Logistics and Supply Chain Management, Revised Ed., Kogan Page, New York, 2015.

[4] Deloitte, How Consumers Are Embracing Sustainability, 2022 [Online]. Available: https://www2.deloitte.com/uk/en/pages/consumer-business/articles/sustainable-consumer.html. (Accessed 28 April 2023).

[5] O. Chkanikova, Sustainable purchasing in food retailing: interorganizational relationship management to green product supply, Bus. Strat. Environ. 25 (7) (Nov. 2016) 478–494.

[6] K. Bandaru, R. Prudden, B. Louw, J. van Eeden, M. du Plessis, Primafruit Industry Meeting, 2023. Evesham, UK. (Accessed 5 September 2023).

[7] A. Hospido, L. Milà I Canals, S. McLaren, M. Truninger, G. Edwards-Jones, R. Clift, The role of seasonality in lettuce consumption: a case study of environmental and social aspects, Int. J. Life Cycle Assess. 14 (5) (2009) 381–391.

[8] R. Parajuli, G. Thoma, M.D. Matlock, Environmental sustainability of fruit and vegetable production supply chains in the face of climate change: a review, Sci. Total Environ. 650 (2019) 2863–2879.

[9] J.I. Macdiarmid, Seasonality and dietary requirements: will eating seasonal food contribute to health and environmental sustainability? Proc. Nutr. Soc. 73 (3) (Aug. 2014) 368–375.

[10] T. Garnett, Wise Moves: Exploring the Relationship between Food, Transport and CO2, 2003. London.

[11] Y. Fan, C. de Kleuver, S. de Leeuw, B. Behdani, Trading off cost, emission, and quality in cold chain design: a simulation approach, Comput. Ind. Eng. 158 (2021) 107442.

[12] M. Du Plessis, J. Van Eeden, L. Goedhals-Gerber, Carbon mapping frameworks for the distribution of fresh fruit: a systematic review, Global Food Secur. 32 (2022) 100607. December 2021.

[13] A. McKinnon, *Decarbonizing Logistics: Distributing Goods in a Low-Carbon World*, First. Croydon, Kogan Page, 2018.

[14] Y. Dong, S.A. Miller, Assessing the lifecycle greenhouse gas (GHG) emissions of perishable food products delivered by the cold chain in China, J. Clean. Prod. 303 (2021).

[15] European Commission Directorate-General for Environment, Field to fork: global food miles generate nearly 20% of all CO2 emissions from food [Online]. Available: https://environment.ec.europa.eu/news/field-fork-global-food-miles-generate-nearly-20-all-co2-emissions-food-2023-01-25_en, 2023. (Accessed 27 October 2023).

[16] Smart Freight Centre, Global Logistics Emissions Council Framework for Logistics Emissions, 2023.

[17] M.J. Du Plessis, A Carbon Mapping Framework for the International Distribution of Fresh Fruit A Standard for Estimating GHG Emissions, Stellenbosch University, 2023.
[18] D. Tranfield, D. Denyer, Producing a Systematic Review, Sage Handb. Organ. Res. Methods, 2009, pp. 672–688.
[19] A. Carlsson-Kanyama, Greenhouse gas emissions in the life cycle of carrots and tomatoes – methods, data and results from a study of the types and amounts of carrots and tomatoes consumed in Sweden, Report Number : LUTFD2-TFEM-97-3019;IMES-EESS-24, 1997. https://rosap.ntl.bts.gov/view/dot/4919,%20osti.gov.
[20] M. Eulálio Neto, I. de A. Nääs, N.D. da S. Lima, Environmental impact of fresh vegetables supply: a case-study in teresina, Brazil, Eur. J. Sustain. Dev. Res. 5 (3) (2021) em0160.
[21] A. Jones, *The Environmental Impacts of Distributing Consumer Goods: a Case Study on Dessert Apples*. search.Proquest, com, 1999.
[22] D. Kittemann, R. McCormick, D.A. Neuwald, Effect of high temperature and 1-MCP application or dynamic controlled atmosphere on energy savings during apple storage, Eur. J. Hortic. Sci. 80 (1) (2015) 33–38.
[23] L. de Kock, V. Russo, H. von Blottnitz, Carbon intensive but decarbonising quickly? Retrospective and prospective Life Cycle Assessments of South African pome fruit, J. Clean. Prod. 212 (2019) 139–150.
[24] E. Svanes, KLIMAT: A Norwegian Research Project. Report from the Banana Case Study, osti.gov, 2012.
[25] J. Chapa, S. Kipp, H. Cai, J.Y. Huang, A comparative life cycle assessment of fresh imported and frozen domestic organic blueberries consumed in Indiana, J. Clean. Prod. 217 (2019) 716–723.
[26] Y. Qin, A. Horvath, What contributes more to life-cycle greenhouse gas emissions of farm produce: production, transportation, packaging, or food loss? Resour. Conserv. Recycl. 176 (2022).
[27] M.J. Du Plessis, J. Van Eeden, L.L. Goedhals-Gerber, The carbon footprint of fruit storage: a case study of the energy and emission intensity of cold stores, Sustainability 14 (13) (Jun. 2022) 7530.
[28] A. Frankowska, H.K. Jeswani, A. Azapagic, Life cycle environmental impacts of fruits consumption in the UK, J. Environ. Manag. 248 (2019).
[29] L. Bin, L. Jiawei, C. Aiqiang, P.E. Theodorakis, Z. Zongsheng, Y. Jinzhe, Selection of the cold logistics model based on the carbon footprint of fruits and vegetables in China, J. Clean. Prod. 334 (2022).
[30] J.A. Dyer, R.L. Desjardins, Energy use and fossil CO2 emissions for the Canadian fruit and vegetable industries, Energy Sustain. Dev. 47 (2018) 23–33.
[31] V. Girgenti, C. Peano, C. Baudino, N. Tecco, From 'farm to fork' strawberry system: current realities and potential innovative scenarios from life cycle assessment of non-renewable energy use and green house gas emissions, Sci. Total Environ. 473–474 (2014) 48–53.
[32] A. Delahaye, et al., Strawberry supply chain: energy and environmental assessment from a field study and comparison of different packaging materials, Int. J. Refrig. 153 (Sep. 2023) 78–89.
[33] E.M. Bell, Environmental Analysis of Food-Energy-Water Systems: Focus on High-Value Crops and Logistics in the United States, University of California, 2018.
[34] C. Rizet, M. Browne, E. Cornelis, J. Leonardi, Assessing carbon footprint and energy efficiency in competing supply chains: review - Case studies and benchmarking, Transport. Res. Transport Environ. 17 (4) (2012) 293–300.
[35] BSI, PAS 2050, Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services, 2011, 2011th ed., BSI Standards Limited, London, 2011.
[36] FPEF, Fresh Produce Export Directory 2022, 2022. Century City, Cape Town.
[37] G. de Beer, A. Paterson, H. Olivier, 160 Years of Export - the History of the Perishable Products Export Control Board, Plattekloof: The Perishable Products Export Control Board (PPECB), 2003.
[38] Eskom, Integrated Report-2021, Johannesburg, 2021.
[39] UK Government, Greenhouse Gas Reporting: Conversion Factors 2022, UK Department for Energy Security and Net Zero & Business Energy and Industrial Strategy, London, 2022.
[40] S.A. Tassou, Y. Ge, A. Hadawey, D. Marriott, Energy consumption and conservation in food retailing, Appl. Therm. Eng. 31 (2–3) (2011) 147–156.
[41] K. Dobers, S. Perotti, A. Fossa, Emission Intensity Factors for Logistics Buildings, 2022.
[42] FAO, Global Food Losses and Food Waste – Extent, Causes and Prevention, Rome, 2011.