



Article

Mini Containers to Improve the Cold Chain Energy Efficiency and Carbon Footprint

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Abstract: The cold chain—the system of refrigerated storage and transport that provides fresh produce or other essentials to be maintained at desired temperatures and environmental conditions—is responsible for substantial energy consumption and greenhouse gas (GHG) emissions, and failures in the cold chain lead to food and energy waste. Here, we introduce the mini container concept as an alternative to conventional reefers, particularly for small growers. Mini containers are relatively small, insulated boxes, with environmental conditions controlled by an electric-powered central driving unit, which can be aggregated as needed and transported by non-refrigerated trucks and trailers. We analyze the energy consumption and GHG emissions for the transport of tomatoes in two cities representing contrasting climates, Phoenix, Arizona, and Chicago, Illinois, for conventional reefers and the proposed mini containers. These two cities provide the opportunity to compare the energy consumption and GHG emissions for the proposed mini containers versus conventional refrigerated transport under extremely different climate conditions. The results show that, as expected in both cases, as the ambient air temperature increases, the energy consumption and GHG emissions also increase. For partial reefer loads less than 72% and 85% for Phoenix and Chicago, respectively, the use of the mini containers reduces energy consumption and GHG emissions because of the reduced volume requiring refrigeration. In general, since the mini containers are fully electrified, their corresponding GHG emissions can be dramatically reduced, and since the fresh produce can be pre-cooled with renewable energy, GHG emissions can even be eliminated.

Keywords: cold chain; carbon footprint; energy efficiency; fresh produce; tomatoes



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1. Introduction

As the population expands, to meet the growing demand, food production must broaden and has to move smoothly from the producers to the consumers. One approach to reduce transportation, waste, and inventory costs along with end-product prices while elevating net profits is investigating and improving each production–consumption process [1]. Hence, to lower costs and deliver food to consumption sites effectively, the cold supply chain concept can be implemented. A temperature-controlled supply chain is a logistics and supply system that consists of a sequence of facilities for sustaining optimum conditions for goods within a specified range of temperatures, from the point of origin to the point of utilization [2]. In short, the series of refrigeration steps along the supply chain

that are followed to keep perishable foods in the given temperature range is referred to as the *cold chain*.

Cold supply chains are especially applied for food products. The food cold chain involves the initial chilling and freezing of foods and the succeeding refrigeration, with foods being refrigerated during post-harvest, delivery, retail distribution, and home storage, to preserve the quality, safety, and shelf-life of foods for end-users [3]. The facilities and equipment in the cold chain may comprise pre-cooling and freezing facilities, freezers, cold storage warehouses, display cabinets, refrigerated trucks, and household refrigerators, which require continuing development and numerous new technologies to improve energy efficiency, reduce greenhouse gas (GHG) emissions, and reduce food waste [4].

Present-day food production–distribution processes have an impact on natural ecosystems and the environment [5]. As an example of food cold chain environmental impact, the provision of food throughout the retail chains constitutes approximately one-third of the UK's total GHG emissions—noting that the production of food is the primary cause of emissions, with transport evaluated to account for 1.8% of the total emissions [5].

It is important to note that approximately one-tenth of all food-related GHG emissions, or about one percent of all GHG emissions in the United States, comes from fresh produce. GHG emissions in the United States account for ~20% of global GHG emissions despite having only five percent of the world's population. Food-related emissions, especially those related to specialty commodities such as fresh produce, are likely to rise as the world's population grows and consumers adopt the consumption patterns of wealthier nations. When it comes to transporting fruits and vegetables, they are more important than most other commodities with respect to their associated carbon footprint. Transportation accounts for 28% of the carbon footprint of fruits and vegetables, even though it accounts for only 11% of the carbon footprint of all food in the United States on average [6].

Post-harvest waste and losses in the vegetable and fruit supply chains are potentially as high as 13 to 38%, before reaching the end-user [6]. Additionally, up to 13% of all short shelf-life foods may be lost due to inadequate refrigeration [7]. Plenty of natural resources, such as water and energy, are incorporated in these food losses, as well as GHG emissions [8]. This constitutes approximately 38% of all energy consumed in the food industry, and refrigeration consumes 8% of the electrical energy used in this industry [9].

The cold chain terminates when the food is placed inside a domestic refrigerator by the end-user. The entire duration of the cold chain depends on the particular product and the chosen market, with a few cold chains being as short as a few hours and others enduring for several months or even years, mostly for frozen food products [10]. The distribution center plays an integral control point in many food cold chain management systems, as it sorts and merges shipments received from many wholesalers and delivers the products according to demand from the retailers. Each step in the food cold chain has an impact on the final quality of the food, and temperature violations may happen at any point, leading to safety concerns or food waste.

Figure 1 depicts a block diagram of the main steps involved in a food cold chain from harvesting (farm) to home storage (domestic refrigeration).

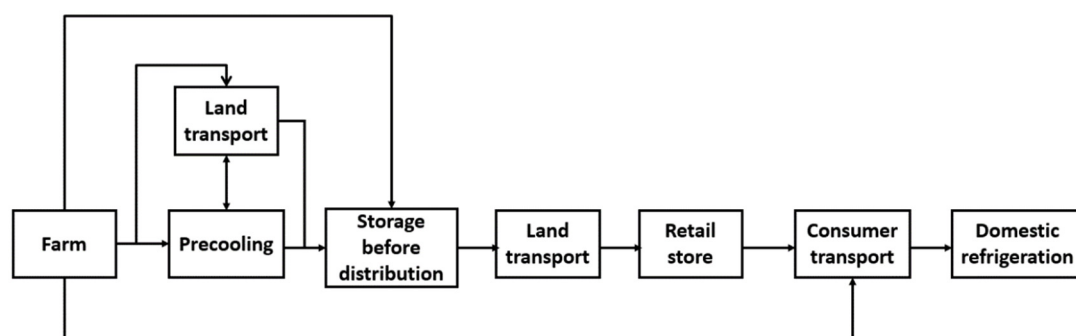


Figure 1. Simplified food cold chain system.

Globally, it is estimated that food production will have to rise by 70% to be able to counter the demand of a rising population by the year 2050 [11]. The depletion in the quantity of fresh fruits and vegetables that were initially meant for human consumption is referred to as food waste or food losses [12]. Internationally, it is estimated that one-third to one-half of all food produced is wasted or lost along post-harvest supply chains, the main source of food waste being packaging, storage, and transportation [13,14]. Losses of fruits and vegetables globally are between 40–50% of which 54% occur in production, storage, or post-harvest handling [15,16]. Each year, we still waste or lose about 30–50% of the consumable parts of food [17]. More than 40% of losses occur at the post-harvest and processing stages due to a lack of infrastructure in the food cold chain and a shortage of knowledge associated with storage technologies at harvest levels in developing nations. However, in developed nations, more than 40% of losses occur at the consumer and retail stages for numerous reasons [18]. One of the countries of particular concern for food waste is the United States. It was evaluated that food wasted by each United States' citizen has increased by 50% since 1995, accounting for more than one-quarter of the total freshwater consumption in the United States and 300 million barrels of oil every year [19]. In the course of packaging, storage, and transportation of fresh agricultural produce, depletion in the quality of the fresh produce also induces food losses. The quality of the fresh produce can be defined as the outstanding characteristics that are desired by the end-user. Customers usually buy fresh produce depending on their biochemical characteristics such as texture, appearance, nutritional value, and flavor [20]. Fresh agricultural produce such as fruits and vegetables are a vital part of human nutrition, as they are principal sources of vitamins, minerals, dietary fibers, carbohydrates, proteins, etc. with immense health benefits [21]. Appropriate in-transit observation of environmental conditions and alteration in the quality attributes of fresh produce during storage and transport can help lower food waste and losses and guarantee the availability and accessibility of fresh fruits and vegetables with elevated nutritional density to the end-users [22]. Figure 2 depicts the food lost or wasted by region and portrays the different stages in the value chain (percent of kcal lost and wasted).

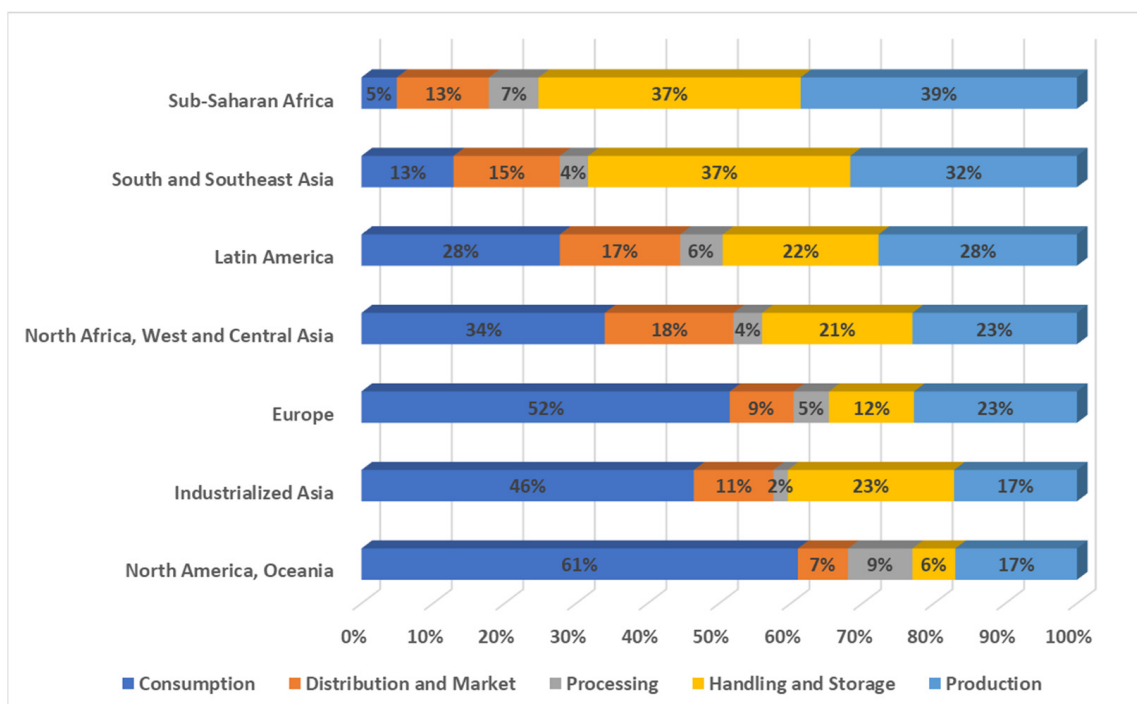


Figure 2. Food loss or waste in developing and developed nations [23].

2. Background

Post-harvest Technologies

The technology used to treat agricultural products after harvest to protect, conserve, process, package, and market them to meet the food and nutritional needs of the consumer population is known as post-harvest technology (PHT). Product quality is maintained or improved during post-harvest processing to make it more marketable. Thus, reducing delivery times, maintaining product quality, reducing shipping costs, and making transportation improvements, in combination with other technological developments, can help reduce post-harvest losses [24].

Post-harvest technology in transportation has long been one of the most stagnant aspects of the cold supply chain. This changed after the FSMA, or the Food Safety Modernization Act, was passed in the United States. The rule mandated vehicle and equipment be capable of maintaining temperatures required for food safety and developed written procedures and regulations to ensure food transportation under adequate temperature conditions. Around the world, controlled atmosphere (CA) technology has been used to extend the shelf-life and maintain the quality of a variety of fresh fruits and vegetables [25].

To maintain the quality of products, a proper combination of temperature and humidity is necessary. For years, data loggers have been used, and the technological evolution now allows the real-time capture and analysis of the required conditions to maximize the quality of the produce [25]. Although GPS, remote monitoring, and temperature sensors have been available for some time, continued improvement benefits the growers to have better control over the downstream traceability for quality control of the produce.

GPS-enabled devices provide constant data of what occurs between loading and unloading of the produce and improve the transparency of the supply chain. Currently, the most common long-haul transportation system is based on a refrigerated van known as a reefer [26], which is not efficient for the transportation of small-scale shipments. This has an impact on small-scale producers who do not require a full reefer trailer to transport their load. The proposed *mini container* approach [27] addresses this shortcoming by splitting the overall load capacity of a freight vehicle into multiple mini containers, each with its own temperature control. This option would give the growers much more control over the temperature of their fresh produce.

The vast majority of refrigerated trucking is carried out with semi-trailers packed with insulated rigid boxes. Furthermore, the most commonly used refrigeration system for cold food transport applications today is the vapor compression refrigeration (VCR) system, powered by dedicated diesel engines. Refrigeration with the VCR cycle offers a wide choice of compressor drive methods. Selection can be based on service, weight, noise, and maintenance requirements, as well as installation costs, environmental considerations, and fuel taxes. The performance and capacity requirements of these systems are generally evaluated at full load. However, in practice, transport refrigeration systems operate with a wide variety of loads. To accommodate changing loads, the refrigeration system is switched on and off, or its capacity is adjusted to maintain the set temperature with reduced efficiency [28].

Vapor compression refrigeration (VCR) systems used in temperature-controlled food transport are responsible for significant GHG emissions. Alternative refrigeration technologies can be used to reduce these emissions. Both direct (i.e., from refrigerant leaks) and indirect (i.e., from fossil fuel combustion) emissions can be important. For example, assuming an annual refrigerant leak of 10% for a large articulated vehicle and a single distribution of refrigerated food using R404A refrigerant, GHG emissions from refrigerant leaks represent 17% of engine emissions from the refrigeration system [28].

An alternative to engine-driven refrigerated transport is battery-powered refrigeration. Bagheri et al. [28] recommended replacing the engine-driven VCR system with a battery-powered VCR system to reduce weight and GHG emissions. Using 7.3 kg of R-404A as refrigerant for the refrigeration unit to maintain the temperature of the products at 4–5 °C,

the cooling process stayed on during product loading and for a couple of hours before the delivery started. According to these calculations, this replacement could reduce mass by a total of 375 kg per trailer, thus reducing GHG emissions from the truck engine by 0.5%. This replacement led to a reduction of 3105 L of diesel fuel for a truck or trailer, which is equivalent to 8320 kg of GHG emissions per year. Extending this to all refrigerated trailers in the world showed that through this replacement, 3.7 billion liters of diesel fuel and 10 million tons of GHG emissions can be avoided each year [28].

In recent years, fruit and vegetable production has become of increasing interest for agricultural research, the United States' economy, and part of a healthier diet of Americans [29]. Tomatoes are one of the most consumed vegetable crops in the world. They rank second after potatoes in terms of quantity and production area [30]. According to FAO (Food and Agriculture Organization) statistics, 180 million tons of fresh tomatoes were produced worldwide in 2019. China leads the production of tomatoes, followed by India, Turkey, and the USA [31]. Fresh tomatoes are produced nationwide in the United States, with California and Florida being the major producers [32].

Based on the above considerations, starting from studies that showed a huge waste in energy and food in the cold supply chain, and the clear need to improve the efficiency of the VCR system, the purpose of this article was to introduce mini containers as a new efficient, cost-effective approach for transporting fresh fruits and vegetables with lower (or zero) GHG emissions especially for partial loads compared to conventional refrigerated transport (reefers). The heat loads on the mini container were calculated for four different types of insulation to help optimize their design. A comparison of the energy intensity and corresponding GHG emissions for two climates, Phoenix, Arizona, USA and Chicago, Illinois, USA, was made for mini containers and conventional reefers transporting tomatoes.

3. Methods

3.1. Mini Containers

The basic idea behind the mini containers is to develop a refrigeration or environmental control unit, called the central driving unit (CDU), that is connected to thermally insulated boxes. This enables almost any vehicle, including pickups, vans, and trailers, to be converted into refrigerated transport. Furthermore, when stationary, the mini containers and their CDUs become a scalable refrigerated warehouse.

Each mini container (MC) would have a traceable ID and would be equipped with sensors to monitor the temperature, humidity level, and environmental conditions. Although the MCs do not contain their own refrigeration system, they would be connected to the CDU that would provide suitable refrigerated and moist air and the desired environmental conditions by utilizing a network of sensors and actuators.

One of the main objectives for the MCs is to fit nontraditional food transportation such as small vans, pickup trucks, and flat trailers. This is possible as the dimensions of the MCs (4 ft × 4 ft × 4 ft, or 1.2 m × 1.2 m × 1.2 m) are designed to efficiently fit such applications. This size benefits small growers in particular, as there is need for farmers to make use of an entire reefer for a relatively small harvest. In other words, the modular nature of the MCs, as shown in Figure 3, means that only the required number of MCs are environmentally controlled to accommodate the harvest.

This reduces the cost, energy consumption, and corresponding GHG emissions relative to an entire conventional reefer. Using the MCs also allows shippers to load different products in different MCs in the same load, recognizing that each MC is individually controlled by the CDU to maintain the required temperature and humidity.

Another advantage of the MC concept is that the CDU which controls all the MCs can be fully powered by batteries that are charged using renewable energy, for example, with solar photovoltaic (PV) panels. The solar PV panels can be located at the farm or at intermediate transit stops to recharge the batteries as needed. This approach reduces or eliminates the GHG emissions from the refrigeration system.

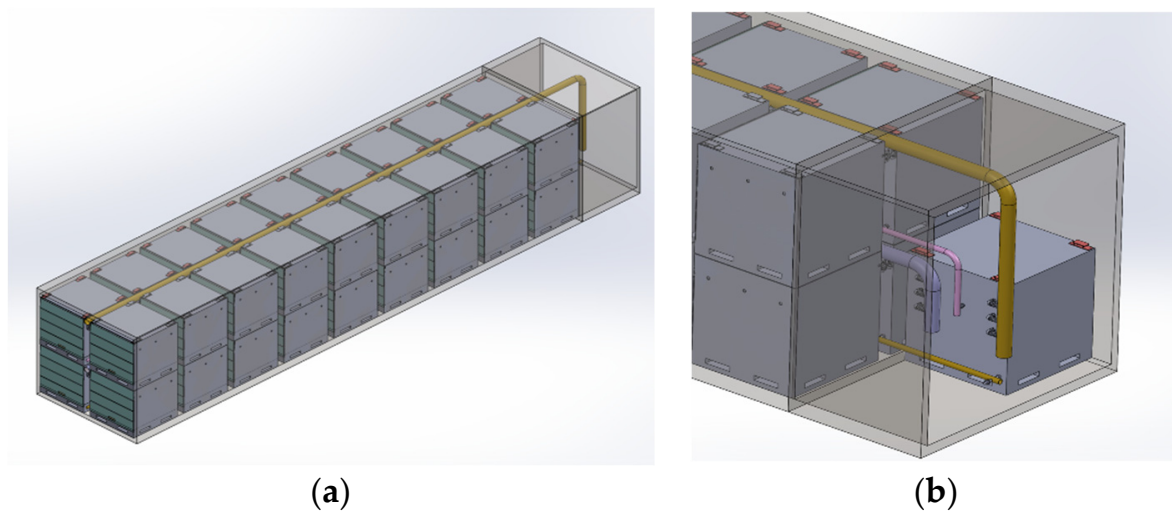


Figure 3. Conceptual design of the mini containers' assembly in a conventional truck: (a) isometric view; (b) central driving unit (CDU).

The conceptual design of the MC system assembly is shown in Figure 3a. A single MC is intended to be an insulated box measuring about 4 ft (1.2 m) in length, width, and height. Equipped with an operable collapsible door, each unit contains a traceability module inside as well as different control valves to ensure adequate operation. A typical 40 feet standard container can hold up to 39 MCs and one central driving unit (CDU) which provides refrigeration by employing a VCR system, as shown in Figure 3b.

In a typical container truck, the MCs can be stacked 2 levels high and in 2 rows of 10 units in length. Airflow to and from the CDU is provided through the return and supply piping, thus maintaining optimal conditions of temperature and relative humidity of the fresh produce in each MC.

Figure 4 presents the basic sketch of an MC in terms of its interactions with the cooled and ambient air, i.e., the airflow inlets and outlets of the system. At point 1, the cooled air from the refrigeration unit is drawn in by the blower and then blown to points 2 and 4 before entering the MC. A mixing valve at point 4 is needed if the wet air coming from the humidifier (point 3) is required to comply with a specified relative humidity condition. Small ethylene, CO₂, and N₂ reservoirs are to be provided (point 5) in case these gases are needed to maintain optimal storage conditions controlled by the sensor module.

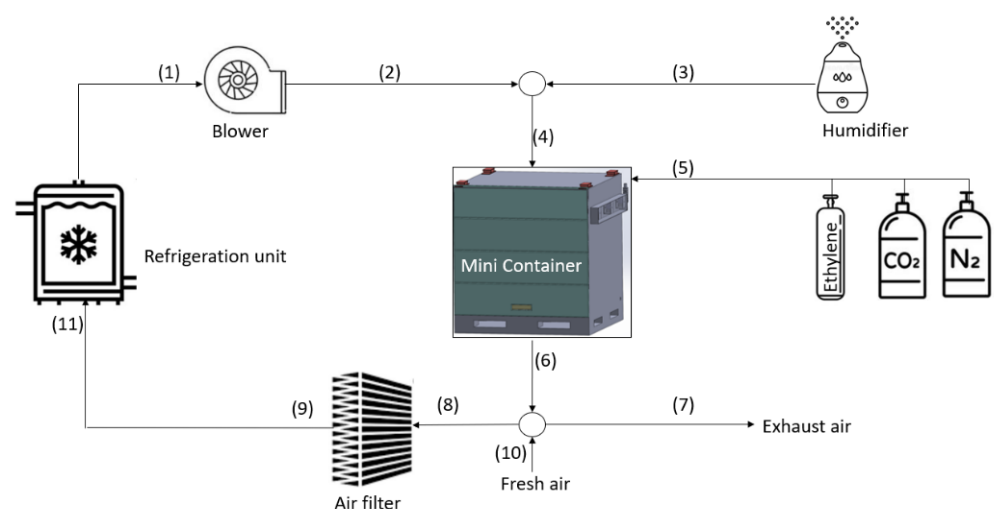


Figure 4. Basic sketch of the mini container (MC) system.

Point 6 represents the airflow coming out of the MC, of which anywhere from a small fraction (e.g., 2%) up to 100% can be exhausted (point 7) and replaced by fresh ambient air at point 10. This mixed air (point 8) passes through a filter and finally, the filtered air at point 9 returns to the refrigeration unit to complete the cycle. The system starts a new cycle as required according to temperature, relative humidity, and CO₂ set points.

3.2. Heat Loads and CO₂ Generation Calculations

Understanding the heat loads on an MC is important in order to size the refrigeration system. The components of the heat load on a typical MC containing fresh produce are the following: conduction from the ambient, new product cooldown, respiration, infiltration, and transpiration.

Conduction load: this is the heat transfer that occurs because of the temperature difference between the inside and outside of the MC, where normally the MC interior is at a lower temperature than the outside air. The conduction load \dot{Q}_{cond} can be calculated by

$$\dot{Q}_{cond} = U * A_s * \Delta T \quad (1)$$

where A_s is the area over which the heat transfer occurs, and ΔT the dry-bulb temperature difference between the ambient air and air inside the MC.

The parameter U is the overall heat transfer coefficient and is calculated by

$$U = \frac{1}{\frac{L_{MC}}{k_{MC}} + \frac{L_{ins}}{k_{ins}} + \frac{1}{h_{conv,ext}} + \frac{1}{h_{conv,in}}} \quad (2)$$

where L_{MC} is the thickness of the MC wall, k_{MC} the wall thermal conductivity (typically made of metal), L_{ins} is the thickness of the thermal insulation, k_{ins} is the thermal conductivity of the insulation, and $h_{conv,ext}$ and $h_{conv,in}$ are the external and internal convective heat transfer coefficients, respectively.

New product cooldown load: this contribution to the heat load represents the sensible heat contained within the product if it enters the MC at a higher temperature than the desired MC temperature, i.e., the desired storage temperature. For the most efficient system, we anticipate that the product would already be pre-cooled, but we recognize that even so, it may still enter the MC at a slightly elevated temperature. Here, we considered the temperature difference to be $\Delta T_{npc} = 1$ °C, and calculated the new product cooldown heat load \dot{Q}_{npc} from

$$\dot{Q}_{npc} = \frac{m_{product} * cp_{product} * \Delta T_{npc}}{t} * \frac{1 \text{ h}}{3600 \text{ s}} \quad (3)$$

where $m_{product}$ and $cp_{product}$ are the mass and specific heat of the product, respectively, and t is the time (1 h) needed for cooling the product to the desired storage temperature.

Infiltration load: the infiltration load is the heat contained within the ambient air that leaks into the MC, since the ambient air is normally at a higher temperature than the MC interior. The infiltration load \dot{Q}_{inf} is calculated by

$$\dot{Q}_{inf} = \frac{Vol \text{ Changes}}{hr} * (Vol_{container}) * (\rho_{air}) * (cp_{air}) * (T_{ambient} - T_{inside}) \quad (4)$$

where $\frac{Vol \text{ Changes}}{hr}$ is the infiltration rate calculated by:

$$\frac{Vol \text{ Changes}}{hr} = \frac{Max \text{ ventilation rate for typical reefer trucks}}{Volume \text{ of the Mini container}} \quad (5)$$

$Vol_{container}$ is the volume of an MC, ρ_{air} and cp_{air} are the density and specific heat, respectively, for the ambient air, $T_{ambient}$ is the dry-bulb temperature of the ambient air, and T_{inside} is the dry-bulb temperature of the air inside the MC.

Transpiration Load: fresh produce normally transpires, or releases moisture to the surrounding air. This results in a negative heat load since the liquid moisture within the produce is vaporized in the air. The transpiration load \dot{Q}_{trans} is calculated by the following equation [33]:

$$\dot{Q}_{trans} = k_t [(P_{sat} * T_{inside}) - (RH * (P_{sat} * T_{inside})) * \frac{1}{10^{12}} * h_{fg}] \quad (6)$$

where k_t is the transpiration coefficient, P_{sat} is the saturation pressure of the water vapor, RH is the relative humidity, and h_{fg} is the latent heat of vaporization.

Product respiration: during respiration, glucose and oxygen combine to form carbon dioxide, water, and heat. The rate at which this chemical reaction takes place varies depending on the type and temperature of the food product. Therefore, the generation of CO_2 in each MC was calculated following the methodology proposed by [34], where a correlation that relates the food's rate of CO_2 generation to its temperature was developed. The CO_2 generation rate as a function of temperature T in $^\circ\text{C}$ is:

$$\dot{m}_{\text{CO}_2} = f \left(\frac{9T}{5} + 32 \right)^g \quad (7)$$

where \dot{m}_{CO_2} is the rate of CO_2 produced per unit mass of the product $\left(\frac{\text{mg}}{\text{kg}\cdot\text{h}} \right)$ and the respiration coefficients f and g for tomatoes are 2.0074×10^{-4} and 2.8350, respectively [34].

Considering the product mass m and the number of MCs ($\#MC$), the total rate of CO_2 generation $\dot{m}_{\text{CO}_2,tot}$ in mg/h then becomes:

$$\dot{m}_{\text{CO}_2,tot} = \#MC \cdot m \cdot f \left(\frac{9T}{5} + 32 \right)^g \quad (8)$$

As for calculating the heat of respiration, for every milligram of CO_2 produced, 10.7 joules of heat are generated [34]. The rate of CO_2 production can then be related to the rate of heat generation of the product through respiration. The resulting correlation gives the product's respiration heat rate \dot{Q}_{resp} in $\frac{\text{W}}{\text{kg}\cdot\text{h}}$ units as follows:

$$\dot{Q}_{resp} = \frac{10.7f}{3600} \left(\frac{9T}{5} + 32 \right)^g \quad (9)$$

Table 1 shows the different conditions, assumptions, and all relevant parameters used in the previous calculations. The value of $COP = 1.25$ was taken from [35] for a 48 ft reefer trailer refrigeration system.

Table 1. All relevant parameters used in the analysis.

Parameter	Value
Ambient temperature in Phoenix ($^\circ\text{C}$)	43
Relative humidity in Phoenix (%)	35
Ambient temperature in Chicago ($^\circ\text{C}$)	20
Relative humidity in Chicago (%)	90
Temperature inside the mini container ($^\circ\text{C}$)	9
Relative humidity inside the mini container (%)	90
L_{MC} (m)	0.006
$k_{MC} \left(\frac{\text{W}}{\text{m}\cdot\text{K}} \right)$	250

Table 1. Cont.

Parameter	Value
L_{ins} (m)	0.053
$h_{conv,ext}$ $\left(\frac{W}{m^2 \cdot K}\right)$	10
$h_{conv,in}$ $\left(\frac{W}{m^2 \cdot K}\right)$	10
$m_{Tomatoes}$ (kg)/MC	272
t (hours)	10
f	2.0074×10^{-4}
g	2.8350
COP	1.25
$cp_{tomatoes}$ $\left(\frac{kJ}{kg \cdot K}\right)$	4.02

4. Results

4.1. Heat Load Distribution for Phoenix, AZ, and Chicago, IL

Figure 5 depicts the distribution of heat loads obtained for a single mini container carrying tomatoes for distribution in Phoenix and Chicago. The results for both locations represent relatively extreme conditions (hot in Phoenix with a total heat load of 0.394 kW and cold in Chicago with a total heat load of 0.347 kW) compared to the documented refrigeration capacity in [35] (from 5.9 kW to 13.5 kW) for a fully loaded conventional reefer. In Phoenix and Chicago, the new product cooldown \dot{Q}_{npc} was the largest component, thus demonstrating the importance of pre-cooling produce as much as possible before transport. The conduction load through the container walls depends, of course, on the type and thickness of thermal insulation (here with $k = 0.025 \text{ W m}^{-1} \text{ K}^{-1}$ taken from [35]), and this value contributed 4% to 12% of the total heat load, respectively. The remaining components were relatively small, but note that the infiltration load may be highly variable depending on the quality of construction for each MC.

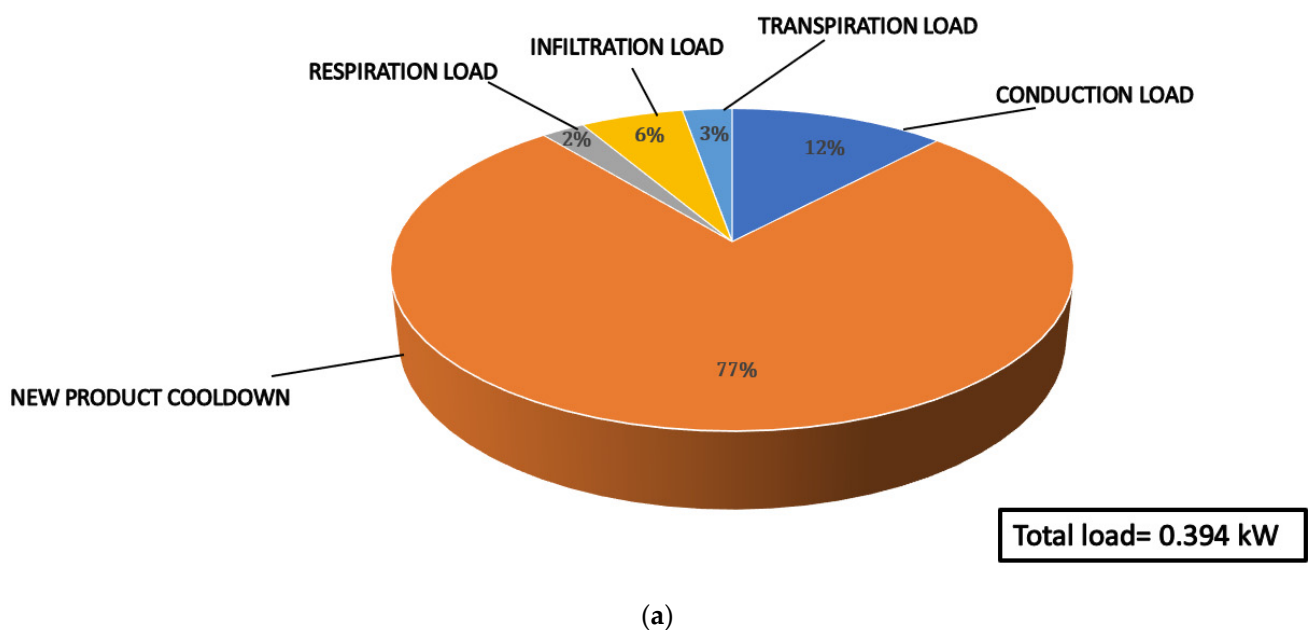


Figure 5. Cont.

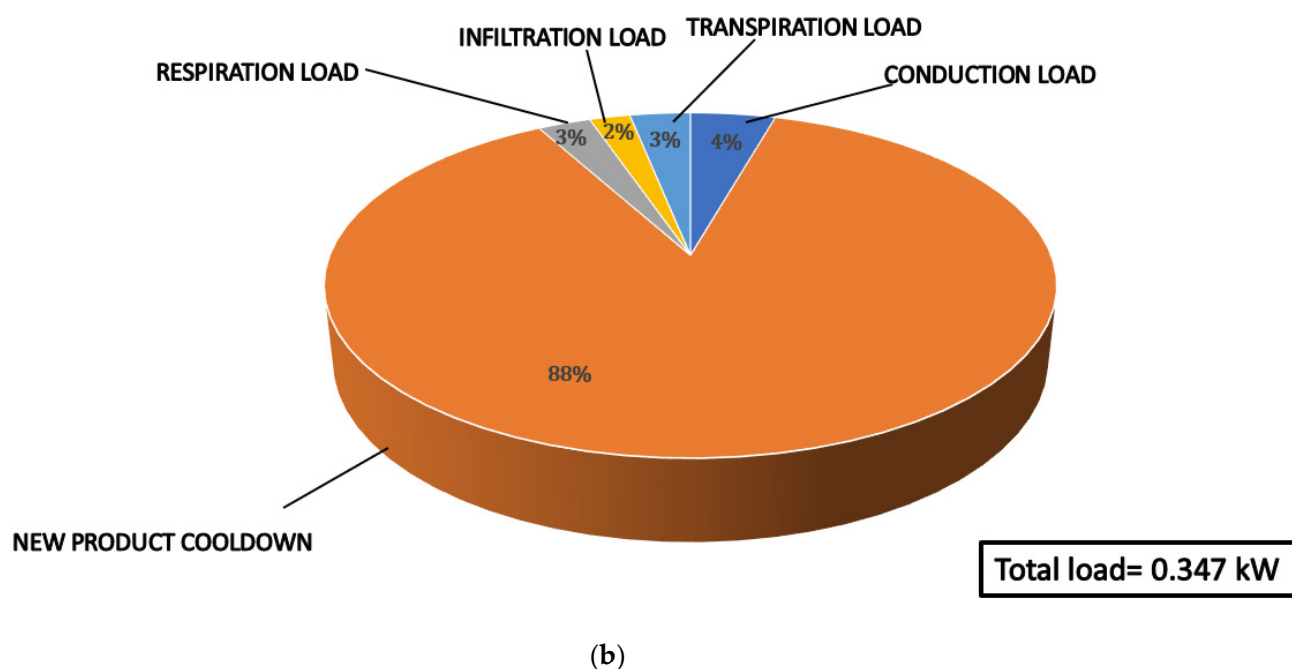


Figure 5. Representative heat load for a single mini container (MC) containing tomatoes in: (a) Phoenix, and (b) Chicago.

The smallest heat load was that from respiration and transpiration, which were found to be only 2% and 3% of the total heat load, respectively. Even within the same type of produce, respiration rates can vary widely. Low respiration rates and slow heat generation commodities such as grapes, apples, cabbage, and potatoes are known for their long shelf lives. Chilling stress, heat stress, physical stress, and atmospheric composition are all other factors that affect fresh produce respiration [36].

4.2. Energy Consumption and GHG Emissions

For their characterization, refrigeration capacity and fuel consumption of conventional reefers are usually measured at full load as per local and international standards. These units are then optimized for a full-load operation, even if in most cases they operate in other modes where performance may be quite different. Several studies have agreed that it is necessary to measure the energy efficiency of the equipment in other operating modes, especially under partial load [37].

Reference [38] presented results of typical refrigeration duty and fuel consumption of self-contained mechanical road refrigeration equipment. The average volume and weight usage of the vehicles were found to be around 53%. In addition, they proposed a measure of energy efficiency in food distribution to be expressed as “energy intensity” that represents fuel consumption on a per pallet kilometer basis, not per vehicle kilometer. They found that for temperature-controlled primary distribution, the average energy intensity was 19.3 mL fuel/pallet-km with a standard deviation of 4.9 mL fuel/pallet-km, whereas for tertiary and mixed distribution, the average energy intensity was 37.3 and 30.1 mL fuel/pallet-km, respectively, with standard deviations of 12.3 and 4.4 mL fuel/pallet-km, respectively.

Regardless of the vehicle type, further data indicated that the average fuel consumption of a typical refrigeration system ranged from 15% to 25% of the vehicle engine’s fuel consumption. Another analysis [38] of refrigerant fuel consumption for hypothetical urban and long-distance distribution estimated the fuel consumption for urban delivery to be 16% higher than that for long-distance deliveries.

Assuming a heating value for diesel of 43.2 MJ/kg, a density of 820 kg/m³, and engine thermal efficiency of 40%, refrigeration energy intensity data [38] can be expressed in kWh/ton-km, considering average volume load, average payload, and percent refrigeration

tion energy consumption. Then, a medium rigid transport (7.5–18 tonne) yields an average refrigeration energy intensity of 0.062 kWh/tonne-km, a large rigid transport (more than 18 tonne) consumes 0.029 kWh/tonne-km on average, and primary and secondary articulated transports (32–28 tonne) yield an average refrigeration energy intensity between 0.016 and 0.025 kWh/tonne-km. We refer to these values below for comparison with the energy intensity of the MCs.

Figure 6 shows the refrigeration energy consumption in kWh per ton-mile and per tonne-km in terms of load percentage for a conventional refrigerated truck (a reefer) compared to MCs with different types of thermal insulation for Phoenix, AZ (Figure 6a) and for Chicago, IL (Figure 6b).

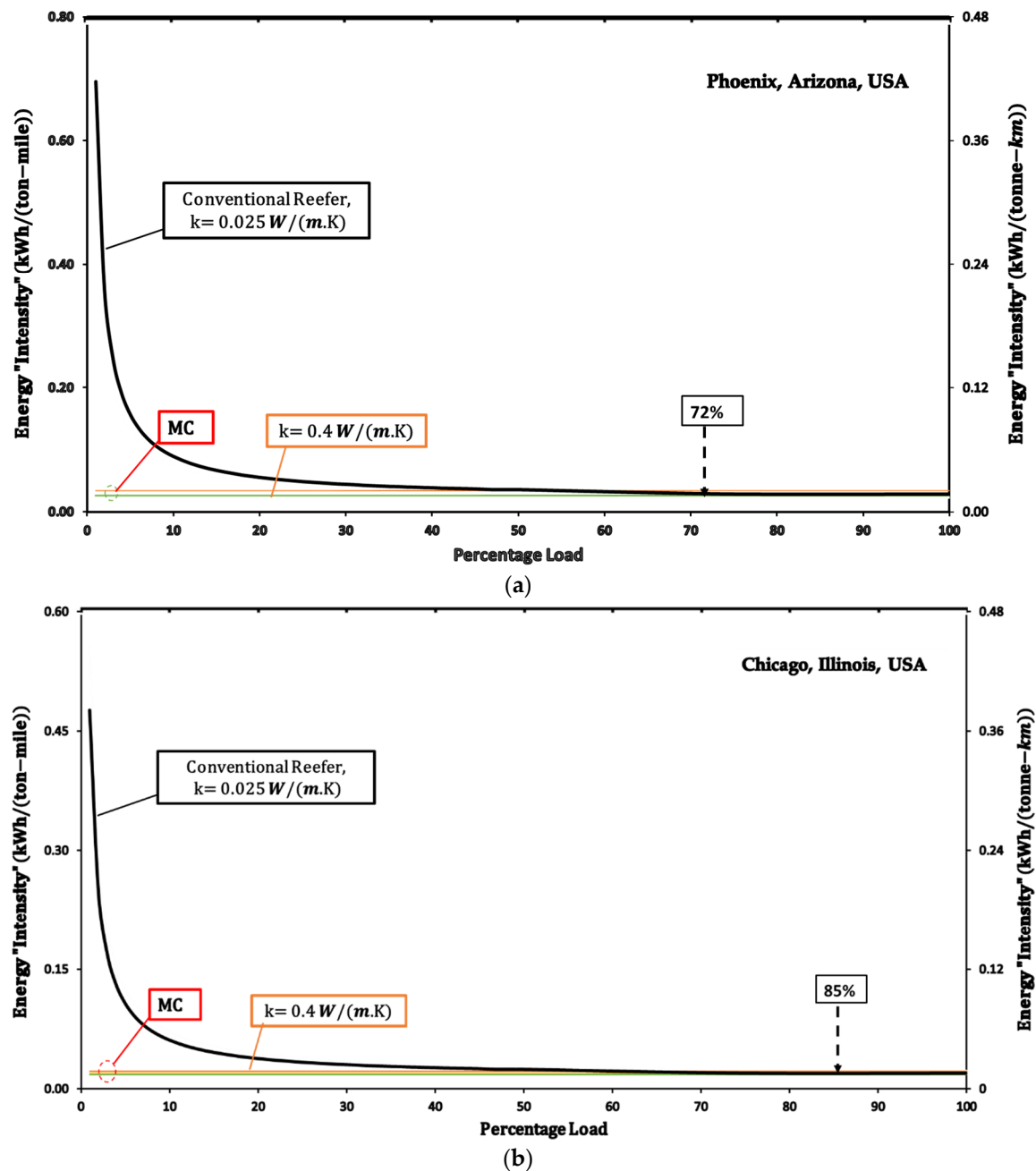


Figure 6. Conventional reefer vs. mini container refrigeration energy consumption, considering tomatoes as the cargo, for: (a) Phoenix, and (b) Chicago, in kWh per ton-mile and kWh per tonne-km.

These curves were obtained from the total thermal load calculations for each case, considering the conduction, new product cooldown, respiration, transpiration, and infiltration heat loads, as well as an average trip of 10 h duration, thus obtaining a relationship between the energy to maintain the refrigerated space at the desired temperature concerning the variable weight of the trucks (percentage load) and a constant average speed of 50 miles/h (80.5 km/h). Results from the conventional reefer truck (thermal insulation with $k = 0.025 \text{ W m}^{-1} \text{ K}^{-1}$) in Phoenix varied from 0.417 kWh/ton-mile for a nearly empty truck down to 0.0170 kWh/tonne-km for the full-load case. The corresponding values for a conventional reefer in Chicago varied from 0.381 kWh/tonne-km for a nearly empty truck down to 0.0155 kWh/tonne-km for the full-load case. Comparing these values to the data reported in [38] for large rigid transport, the average energy intensity reported (0.029 kWh/tonne-km) corresponds to the energy consumption of a 25% loaded conventional reefer considered in this analysis. This difference may be due to different ambient temperatures, which were not specified in the cited reference.

On the other hand, the energy consumption curves for the MCs in Phoenix yielded values of 0.023, 0.0182, 0.0181, and 0.0177 kWh/tonne-km for polyurethane insulation ($k = 0.04 \text{ W m}^{-1} \text{ K}^{-1}$), extruded polystyrene ($k = 0.04 \text{ W m}^{-1} \text{ K}^{-1}$), polystyrene ($k = 0.025 \text{ W m}^{-1} \text{ K}^{-1}$), and aerogel ($k = 0.013 \text{ W m}^{-1} \text{ K}^{-1}$), respectively. These energy consumption values compare reasonably well with the average energy intensity range from 0.016 to 0.025 kWh/tonne-km for the 38 tonne of articulated transport [38].

As can be seen in Figure 6, the energy consumption curve for the conventional reefer presents a decreasing trend as the load percentage increases; that is, the highest energy consumption concerning the weight and distance traveled occurred at the emptiest state. Although the load per product transported is lower, the total internal volume of the container must be kept at the same temperature established as the set point. Therefore, additional energy needed to maintain the cargo temperature is used for temperature control of the void space in the container.

On the other hand, in the case of the proposed truck loaded with individual refrigerated MCs, it can be observed that the trend of energy consumption was constant regardless of the load level of the truck, which is consistent with the concept of the MC since energy is only required for refrigeration depending on the number of MCs transported, without wasting unnecessary cooling in the empty portions of the transport truck.

As can be noted, the use of MCs could reduce the energy consumption for partial loads up to a load percentage of approximately 72% for Phoenix and 85% for Chicago. Above these percentages, the traditional reefer presents a lower energy consumption for Phoenix and Chicago if polyurethane insulation ($k = 0.04 \text{ W m}^{-1} \text{ K}^{-1}$) is used as thermal insulation for the MCs. For Phoenix and Chicago, however, if extruded polystyrene ($k = 0.04 \text{ W m}^{-1} \text{ K}^{-1}$), polystyrene ($k = 0.025 \text{ W m}^{-1} \text{ K}^{-1}$), or aerogel ($k = 0.013 \text{ W m}^{-1} \text{ K}^{-1}$) are used as thermal insulation, then the MCs always have a lower energy intensity than the conventional reefers, although the energy intensity values are close. In general, despite considering different types of MC insulation, which reduce heat transfer as the thermal conductivity decreases, the performance of the conventional reefer results in lower energy consumption at high load percentages.

For hot climates such as Phoenix, it appeared that improving the thermal insulation further leads to diminishing improvements in energy intensity relative to conventional reefers. Rather, additional improvements in energy intensity can be achieved through improving the energy efficiency of the refrigeration system. This will be explored in future work.

Figure 7 represents the indirect GHG refrigeration emissions for tomatoes in Phoenix and Chicago. Not surprisingly, the carbon emission intensity was highest for minimally loaded conventional reefers and decreases with increasing load percentage. For the MCs, GHG emissions are identically zero as all power to the CDU was assumed to come from batteries, which are pre-charged using renewable resources at the beginning of the trip.

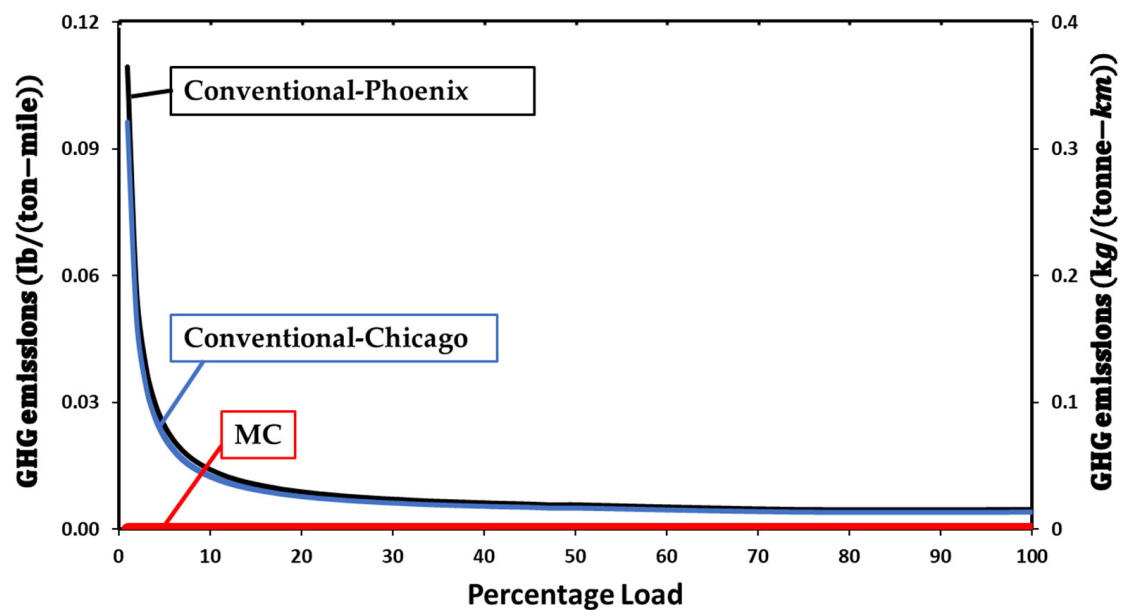


Figure 7. Indirect GHG refrigeration emissions for tomatoes in kg per tonne-km and lb per ton-mile in Phoenix and Chicago.

As a comparison, ref. [39] applied an emissions factor for diesel of 2.668 kg CO₂ per liter. They found that depending on the vehicle used and the type of distribution, the CO₂ emissions varied between 48 g CO₂/pallet-km for ambient single-drop primary and secondary distribution with vehicles above 38 tonne, to 115 g CO₂/pallet-km for multi-drop temperature-controlled tertiary and mixed distribution with vehicles from 7.5 to 18 tonne. These results neglected direct emissions from refrigerant leakage, although it is well-known that transport refrigeration systems can lead to higher refrigerant leakage, for they operate in a more rugged environment than stationary systems. From [39], for conventional refrigerated transport, the GHG emissions varied between 0.069 kg CO₂/tonne-km for ambient single-drop primary and secondary distribution, to 0.295 kg CO₂/tonne-km for multi-drop temperature-controlled tertiary and mixed distribution with vehicles. These results were within or exceeded the range for conventional reefers shown in Figure 7.

5. Conclusions

This article introduced the mini container concept as a promising approach that can improve the transportation of fresh produce using clean energy. Mini containers are $4 \times 4 \times 4$ ft³ insulated boxes that enable traceable, controlled environments to be maintained corresponding to the fresh produce in each mini container. Refrigeration and other environmental conditions are maintained by a separate central driving unit powered by batteries that can be charged via renewable energy. A preliminary analysis of the heat load on a mini container loaded with fresh tomatoes in Phoenix, Arizona, and Chicago, Illinois revealed that the largest component of the heat load is the “new product cooldown” required to reduce the temperature of the produce from its initial state to the desired storage temperature, demonstrating the importance of pre-cooling fresh produce to minimize refrigeration energy requirements during transportation. A comparison of the refrigeration energy intensity and greenhouse gas (GHG) emissions between conventional reefers and the mini containers showed that partially loaded reefers have higher refrigeration energy intensities, especially for cold climates such as Chicago. Indirect GHG emissions, on the other hand, could be identically zero for the mini containers because of the potential for pre-cooling using renewable energy.

The main limitation in this work was to find related data to compare with from the literature. Some of the published data, the conditions and assumptions for the calculations, and the specifications of the vapor compression refrigeration system that had been used in

the literature were hard to obtain, especially for transport of tomatoes. We were not able to perform experiments to validate our results, so instead, we compared our results with the literature which showed that the energy intensity we calculated is within the range that has been previously reported.

Future work can address improving the energy efficiency of the mini containers even further through innovations in controls, the refrigeration cycle, and cold distribution.

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Nomenclature

A_s	Area over which the heat transfer occurs (m^2)
COP	Coefficient of performance
cp_{air}	Specific heat of ambient air ($\frac{kJ}{kg \cdot K}$)
$cp_{product}$	Specific heat of the product ($\frac{kJ}{kg \cdot K}$)
f, g	Respiration coefficients for tomatoes (-)
$h_{conv,ext}$	External convective heat transfer coefficient ($\frac{W}{m^2 \cdot K}$)
$h_{conv,in}$	Internal convective heat transfer coefficient ($\frac{W}{m^2 \cdot K}$)
h_{fg}	Latent heat of vaporization ($\frac{kJ}{kg}$)
k_{ins}	Thermal conductivity of the insulation ($\frac{W}{m \cdot K}$)
k_{MC}	Wall thermal conductivity (typically made of metal) ($\frac{W}{m \cdot K}$)
k_t	Transpiration coefficient ($\frac{ng}{kg \cdot s \cdot pa}$)
L_{ins}	Thickness of the thermal insulation (m)
L_{MC}	Thickness of the mini container (MC) wall (m)
\dot{m}_{CO_2}	Rate of CO_2 produced per unit mass of the product ($\frac{mg}{kg \cdot h}$)
$m_{product}$	Mass of the product (kg)
P_{sat}	Saturation pressure of the water vapor (Pa)
\dot{Q}_{cond}	Conduction load on a mini container (kW)
\dot{Q}_{inf}	Infiltration load on a mini container (kW)
\dot{Q}_{npc}	New product cooldown heat load (kW)
\dot{Q}_{resp}	Product respiration heat rate (kW)
\dot{Q}_{trans}	Transpiration load (kW)
RH	Relative humidity (-)
t	Time needed for cooling the product to the desired Storage temperature (h).
$T_{ambient}$	Dry-bulb temperature of the ambient air ($^{\circ}C$)
T_{inside}	Dry-bulb temperature of the air inside the MC ($^{\circ}C$)
U	Overall heat transfer coefficient ($\frac{W}{m^2 \cdot K}$)
ΔT	Dry-bulb temperature difference between the ambient and inside the MC ($^{\circ}C$)
ρ_{air}	Density of ambient air ($\frac{kg}{m^3}$)

References

1. Etemadnia, H.; Goetz, S.J.; Canning, P.; Tavallali, M.S. Optimal wholesale facilities location within the fruit and vegetables supply chain with bimodal transportation options: An LP-MIP heuristic approach. *Eur. J. Oper. Res.* **2015**, *244*, 648–661. [\[CrossRef\]](#)
2. Tsai, K.-M.; Pawar, K.S. Special Issue on Next-Generation Cold Supply Chain Management: Research, Applications and Challenges. *Int. J. Logist. Manag.* **2018**, *29*, 786–791. [\[CrossRef\]](#)
3. James, S.J.; James, C. The food cold-chain and climate change. *Food Res. Int.* **2010**, *43*, 1944–1956. [\[CrossRef\]](#)
4. Zhao, H.; Liu, S.; Tian, C.; Yan, G.; Wang, D. An overview of current status of cold chain in China. *Int. J. Refrig.* **2018**, *88*, 483–495. [\[CrossRef\]](#)
5. Soussana, J.-F. Research priorities for sustainable agri-food systems and life cycle assessment. *J. Clean. Prod.* **2014**, *73*, 19–23. [\[CrossRef\]](#)
6. Global Food Losses and Food Waste. Available online: <http://www.fao.org/3/mb060e/mb060e00.htm> (accessed on 14 September 2021).
7. The Role of Refrigeration in Worldwide Nutrition—Cool Coalition. Available online: <https://coolcoalition.org/the-role-of-refrigeration-in-worldwide-nutrition/> (accessed on 14 September 2021).
8. Repice, C.; Stumpf, A. Energy Efficiency in Transport Refrigeration. Available online: <https://iifiir.org/en/fridoc/energy-efficiency-in-transport-refrigeration-130158> (accessed on 14 September 2021).
9. Zilio, C. Moving toward sustainability in refrigeration applications for refrigerated warehouses. *HVACR Res.* **2014**, *20*, 1–2. [\[CrossRef\]](#)
10. Gogou, E.; Katsaros, G.; Derens, E.; Alvarez, G.; Taoukis, P.S. Cold chain database development and application as a tool for the cold chain management and food quality evaluation. *Int. J. Refrig.* **2015**, *52*, 109–121. [\[CrossRef\]](#)
11. Tilman, D.; Balzer, C.; Hill, J.; Befort, B.L. Global food demand and the sustainable intensification of agriculture. *Proc. Natl. Acad. Sci. USA* **2011**, *108*, 20260–20264. [\[CrossRef\]](#)
12. Morris, K.J.; Kamarulzaman, N.H.; Morris, K.I. Small-scale postharvest practices among plantain farmers and traders: A potential for reducing losses in rivers state, Nigeria. *Sci. Afr.* **2019**, *4*, e00086. [\[CrossRef\]](#)
13. Arias Bustos, C.; Moors, E.H.M. Reducing post-harvest food losses through innovative collaboration: Insights from the Colombian and Mexican avocado supply chains. *J. Clean. Prod.* **2018**, *199*, 1020–1034. [\[CrossRef\]](#)
14. Lundqvist, J.; Fraiture, C.; Molden, D.; Berndes, G.; Berntell, A.; Falkenmark, M. *Saving Water: From Field to Fork: Curbing Losses and Wastage in the Food Chain*; Draft for CDS, May 2008. SIWI Paper 13; Stiftelsen Stockholm International Water Institute: Stockholm, Sweden, 2008; pp. 5–6.
15. Office of Assistant Director-General (Natural Resources Management and Environment Department). *Food Wastage Footprint Impact on Natural Resources: Summary Report*; FAO: Rome, Italy, 2013.
16. dos Santos, S.F.; de Cardoso, R.C.V.; Borges, Í.M.P.; e Almeida, A.C.; Andrade, E.S.; Ferreira, I.O.; do Ramos, L.C. Post-harvest losses of fruits and vegetables in supply centers in Salvador, Brazil: Analysis of determinants, volumes and reduction strategies. *Waste Manag.* **2020**, *101*, 161–170. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Godfray, H.C.J.; Beddington, J.R.; Crute, I.R.; Haddad, L.; Lawrence, D.; Muir, J.F.; Pretty, J.; Robinson, S.; Thomas, S.M.; Toulmin, C. Food Security: The Challenge of Feeding 9 Billion People. *Science* **2010**, *327*, 812–818. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Nellemann, C. *The Environmental Food Crisis: The Environment's Role in Averting Future Food Crises: A UNEP Rapid Response Assessment*; United Nations Environment Programme, GRID-Arendal, Eds.; UNEP: Arendal, Norway, 2009; ISBN 978-82-7701-054-0.
19. Kantor, L.S.; Lipton, K.; Manchester, A.; Oliveira, V. Estimating and Addressing America's Food Losses. *Food Rev. Natl. Food Rev.* **1997**, *20*, 2–12.
20. Mampholo, B.M.; Sivakumar, D.; Thompson, A.K. Maintaining overall quality of fresh traditional leafy vegetables of Southern Africa during the postharvest chain. *Food Rev. Int.* **2016**, *32*, 400–416. [\[CrossRef\]](#)
21. Bradford, K.J.; Dahal, P.; Van Asbrouck, J.; Kunusoth, K.; Bello, P.; Thompson, J.; Wu, F. The dry chain: Reducing postharvest losses and improving food safety in humid climates. *Trends Food Sci. Technol.* **2018**, *71*, 84–93. [\[CrossRef\]](#)
22. Canadian Food Inspection Agency (Government of Canada). Food Safety Enhancement Program. Available online: <https://inspection.canada.ca/food-safety-for-industry/archived-food-guidance/safe-food-production-systems/food-safety-enhancement-program/eng/1299855874288/1299859914238> (accessed on 14 September 2021).
23. Gustavsson, J.; Cederberg, C.; Sonesson, U.; van Otterdijk, R.; Meybeck, A. *Global Food Losses and Food Waste: Extent, Causes and Prevention*; Food and Agriculture Organization of the United Nations (FAO): Rome, Italy, 2011; pp. 4–10.
24. Heap, R. Refrigerated Transport: Progress Achieved and Challenges to Be Met, 16th Informatory Note on Refrigerating Technologies. Available online: <https://iifiir.org/en/fridoc/refrigerated-transport-progress-achieved-and-challenges-to-be-met-123990> (accessed on 14 September 2021).
25. LeBlanc, D. Land transportation of fresh fruits and vegetables: An update. *Stewart Postharvest Rev.* **2005**, *1*, 1–7. [\[CrossRef\]](#)
26. What is Reefer in Shipping Terms? Available online: <https://www.porttechnology.org/news/what-is-reefer-in-shipping-terms/> (accessed on 28 March 2022).
27. Villalobos, J.R. Systems, Methods, and Apparatuses for Implementing Aggregable, Environment-Controlled Minicontainers for the Efficient Logistics of Perishable Products. U.S. Patent PCT/US21/37432, 15 June 2021.

28. Bagheri, F.; Fayazbakhsh, M.A.; Bahrami, M. Real-time performance evaluation and potential GHG reduction in refrigerated trailers. *Int. J. Refrig.* **2017**, *73*, 24–38. [CrossRef]
29. Sacks, R.; Yi, S.S.; Nonas, C. Increasing Access to Fruits and Vegetables: Perspectives From the New York City Experience. *Am. J. Public Health* **2015**, *105*, e29–e37. [CrossRef]
30. John, F.M.; Patrick, O.A.; Moses, S.A. Effect of maturity stage on quality and shelf life of tomato (*lycopersicon esculentum* mill) using refrigerator storage system. *Eurasian J. Agric. Res.* **2020**, *4*, 22.
31. FAOSTAT. Available online: <http://www.fao.org/faostat/en/#home> (accessed on 14 September 2021).
32. Ask IFAS—Powered by EDIS. Available online: <https://edis.ifas.ufl.edu/> (accessed on 14 September 2021).
33. Available online: <https://AshraeChapter19ThermalPropertiesofFoods.pdf> (accessed on 28 March 2022).
34. Becker, B.R. Transpiration and Respiration of Fruits and Vegetables. In Proceedings of the Meeting of Commission C2 with Commissions B2, D1 and D2-3, of the International Institute of Refrigeration, Lexington, KY, USA, 2–4 October 1996; Institut International du Froid: Paris, France, 1996; ISBN 0-929355-80-6.
35. Ingersoll-Rand Company. *Genuine Parts Catalog. The Finest Parts Engineered with Unmatched Quality and Reliability*; Termo King, 2010. Available online: <http://www.thermoking.comp> (accessed on 28 March 2022).
36. Lafaye de Micheaux, T.; Ducoulombier, M.; Moureh, J.; Sartre, V.; Bonjour, J. Experimental and numerical investigation of the infiltration heat load during the opening of a refrigerated truck body. *Int. J. Refrig.* **2015**, *54*, 170–189. [CrossRef]
37. Tassou, S.A.; De-Lille, G.; Ge, Y.T. Performances of transport refrigeration units at partial load; testing methodology and comparison with performances at full load. In Proceedings of the 24th IIR International Congress of Refrigeration, Yokohama, Japan, 16–22 August 2015. Available online: <https://iifir.org/fr/fridoc/31667> (accessed on 14 September 2021).
38. Tassou, S.; De-Lille, G.; Ge, Y. Food transport refrigeration—Approaches to reduce energy consumption and environmental impacts of road transport. *Appl. Therm. Eng.* **2009**, *29*, 1467–1477. [CrossRef]
39. Parfitt, J.; Barthel, M.; Macnaughton, S. Food waste within food supply chains: Quantification and potential for change to 2050. *Phil. Trans. R. Soc. B* **2010**, *365*, 3065–3081. [CrossRef] [PubMed]