

Assessing the lifecycle greenhouse gas (GHG) emissions of perishable food products delivered by the cold chain in China



Yabin Dong^{a, *}, Shelie A. Miller^{a, b}

^a Center for Sustainable Systems, School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, United States

^b Department of Civil and Environmental Engineering, University of Michigan, Ann Arbor, MI, United States

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ABSTRACT

The cold chain (refrigerated supply chain) preserves the value of perishable products and it is rapidly expanding in China. The environmental impacts of cold chain expansion are of increasing concern but are not well-studied. This study investigated the lifecycle GHG emissions of vegetables, fruit, meat, and aquatic products delivered by the cold chain in China. A lifecycle assessment (LCA) framework based on 1 kg edible product consumed is used. Monte Carlo simulation is applied to characterize the variability of the simulation and sensitivity analysis for 22 parameters are conducted. We found that refrigerated warehouses, the 1st refrigerated transportation, and the retail stage represent more than 50% of post-agriculture cold chain emissions. The results also show that the energy usage of the cold chain constitutes an average of 61% GHG emissions in four fruit/vegetable scenarios, while emissions associated with food losses and wastes are the largest in meat/aquatic scenarios. By accumulating the post-agriculture cold chain GHG emissions, the results show that the cold chain activities can potentially constitute 1–3% of overall emissions in China based on 2018's level.

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1. Introduction

Mitigating GHG emissions is critical to prevent climate change and assessing GHG emissions can effectively support industries to make sustainable decisions. The cold chain uses refrigeration technologies to prevent spoilage and preserve the value of perishable food from production to consumption (Global Cold Chain Alliance). The cold chain industry is growing rapidly in developing countries such as China. The Chinese cold chain market size is expected to grow from RMB 276.37 billion in 2019 to over RMB 500 billion in 2026 (ResearchMarkets, 2020). The rapid expansion of cold chain will inevitably generate greenhouse gas (GHG) emissions (Zhao et al., 2018), (Hu et al., 2019). However, the potential GHG emissions of using the cold chain to deliver perishable food products are not well-studied. Thus, the purpose of this paper is to evaluate the lifetime GHG emissions of non-processed high-value perishable food products (i.e. meat, aquatic, fruit, and vegetables) that are delivered by the cold chain in China.

GHG emissions associated with food products' cold chain come from refrigerant leakage and energy consumption (Dong et al.,

2020), (Hoang et al., 2016). Firstly, traditional refrigerants including chlorofluorocarbon (CFCs), hydrochlorofluorocarbon (HCFCs), and hydrofluorocarbon (HFCs) can leak directly into the environment and cause severe environmental impacts (Xue et al., 2019; Heard and Miller, 2016; United Nations Environment Programme, 2018). CFCs (e.g., R12) and HCFCs (e.g., R22) are being phased out under the Montreal Protocol due to the ozone depletion effect (United Nations Treaty Collection, 1987). Developed countries and developing countries will completely phase out HCFCs by 2030 and 2040, respectively (Shaik and Babu, 2017; US Environmental Protection Agency, 2020; Zhang et al., 2019a). HFCs (e.g., R404a and R134a) are widely used in refrigeration systems to substitute R22. However, most HFCs have high global warming potentials (GWP) and are restricted by the Kigali Amendment (United Nations Treaty Col, 2016; Zemel et al., 2013; Heredia-Aricapa et al., 2020). Developed countries need to phase down HFCs by 85% of the baseline year¹ by 2036 (The European FluoroCarbons Technical Committee), (UNEP, 2016). Article5²

¹ Average production/consumption of HFCs in 2011–2013 + 15% of HCFC baseline production/consumption (The European FluoroCarbons Technical Committee), (UNEP, 2016).

² Article 5: Special situation of developing countries (UN Environment Program).

* Corresponding author.

E-mail address: dyabin@umich.edu (Y. Dong).

Abbreviations

CFC	chlorofluorocarbon
CO ₂ eq	CO ₂ equivalent
DC	Distribution center
FLW	Food losses and wastes
GHG	Greenhouse gas
GWP	Global warming potential
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HT	High-temperature
kg CO ₂ eq/kg consumption	kg of CO ₂ equivalent emissions per kg of food consumed
LCA	Lifecycle assessment
LT	Low-temperature
MT	Medium-temperature
RW	Refrigerated warehouse

Group 1 and Article 5 Group 2 developing countries³ need to phase down HFCs by 80% and 85% of the baseline year⁴ by 2040 and 2045, respectively (The European FluoroCarbons Technical Committee), (UNEP, 2016). Secondly, the energy consumption of refrigeration also leads to significant GHG emissions. In refrigerated storage facilities, energy consumption is mainly from electricity consumption. According to the Green Cooling Initiative, refrigeration is responsible for around 5% of the world's electricity consumption corresponding to 2.5% of global GHG emissions in 2018 (Green Cooling Initiative, 2020), (International Energy Agency (IEA)). In refrigerated vehicles, energy consumption is mainly from fuel consumption, and vehicle engines drive the refrigeration system (Tassou et al., 2009). In refrigerated vehicles, energy consumption can be up to 86% of total emissions (Wu et al., 2013). Overall, the combined emissions from leakage and energy consumption of major cold chain activities are estimated to account for 1–3.5% of GHG emissions in the world, 70–80% of which is due to energy consumption (Heard and Miller, 2016), (Green Cooling Initiative, 2020), (Garnett, 2007), (James and James, 2010).

In addition to refrigerant leakage and energy consumption, GHG emissions of the food cold chain are also associated with food losses and wastes (FLW) (Hu et al., 2019), (Dong et al., 2020). Food losses refer to the lost edible food quantity during the supply chain, whereas food wastes occur at the end of the supply chain related to retailers and consumers (Hu et al., 2019), (Blakeney, 2019). According to James (James and James, 2010), over 200 million tonnes of perishable products could be preserved in developing countries if they were properly stored. FLW leads to the waste of invested energy and carbon in agriculture activities (Hu et al., 2019). The cold chain can prolong the shelf life of perishable products to reduce food and embodied carbon losses. From a system perspective, (Hu et al., 2019), (Dong et al., 2020), (Heard and Miller, 2018) pointed out a tradeoff between using the cold chain to prevent food losses and the emissions generated from using refrigeration facilities.

Hence, it is critical to examine all three emission causes of the food cold chain: refrigerant leakage, energy consumption, and FLW related emissions.

As a standard method to evaluate GHG emissions, life cycle assessment (LCA) tracks the lifetime of a product (or a service) from production to disposal, which can systematically evaluate the total environmental impacts (Finnveden et al., 2009; Rebitzer et al., 2004; Pennington et al., 2004). In evaluating the cold chain industry, Hoang et al. (Hoang et al., 2016) conducted an LCA study to compare the chilling and super-chilling technologies for the salmon cold chain. The study is based on 1 kg of consumed salmon at the end of the cold chain with a European geographical focus. Wu et al. (Wu et al., 2019) investigated the environmental impacts of the orange cold chain and used computational fluid dynamics (CFD) to trace the historical temperature of fresh oranges produced in South Africa and exported to Switzerland. To investigate the GHG emissions of introducing cold chain into developing countries, Heard and Miller (Heard and Miller, 2019) simulated the GHG emissions of the agricultural cold chain in sub-Saharan Africa assuming development pathways similar to North America and Europe. They found that the GHG emissions at the system level (from agricultural production to the pre-retail stage) may increase by 10% or decrease by 15% depending on the diet structure (proportion of meat consumption) in different scenarios.

Regarding the cold chain in China, Zhao et al. (Zhao et al., 2018) and Dong et al. (Dong et al., 2020) reviewed the current status and discussed the environmental impacts. Both studies found that cold chain facilities are insufficient in China. The refrigerated warehouse capacity per capita in China was 0.132 m³ in 2018, while that data for the US and UK is 0.49 and 0.44 (Salin, 2018). The distribution of refrigerated warehouses is uneven and more developed regions tend to have more cold chain facilities (Dong et al., 2020). Although the current cold chain facilities are still inadequate in China, the growing economy and improved living standards drive its rapid expansion. The refrigerated warehouse capacity increased by 38% from 2014 to 2018 in China, while the increase rate is 14% in the US (Salin, 2018). Simultaneously, the concerns of environmental impacts resulted from using cold chain in food logistics arise. Hu et al. (Hu et al., 2019) took China as an example and investigated the tradeoff between using a cold chain for meat, milk, and aquatic products and environmental impacts. They found that increasing the electricity input to the refrigeration systems can reduce the overall cold chain emissions when considering food loss reduction. However, without considering the refrigerant leakage and emissions from refrigerated transportation, the study of Hu can only partially represent the emissions of the food cold chain in China.

Overall, the attention on the environmental impacts of the cold chain for food products is rising in China. However, most cold chain studies still focus on cold chain management or optimization (Hanet et al., 2020; Dai et al., 2019; Zhang et al., 2019b; Zhang et al., 2019c), while few studies (Schmidt Rivera et al., 2014) analyze the lifecycle emissions of food products specifically delivered by the cold chain in China. Therefore, this study aims to fill this knowledge gap and evaluates the lifetime GHG emissions of four types of unprocessed food products (i.e. fruit, vegetables, meat, and aquatic) from production to consumption with the cold chain being responsible for the delivery. One major challenge of conducting an LCA study is data availability. Existing literature contains assumptions based on known data, which may be from a different country or a different application context (Hu et al., 2019), (Heard and Miller, 2019) (Xue et al., 2017). In our study, we have a finer resolution of lifecycle inventory data (Supplementary Materials) to compare with existing studies (Hoang et al., 2016), (Heard et al., 2019). For instance, we model the quantity of food losses along the cold chain as a function of storage time and temperature

³ Article 5 Group 1: parties not in Group 2; Article 5 Group 2: Bahrain, India, the Islamic Republic of Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia and the United Arab Emirates (The European FluoroCarbons Technical Committee), (UNEP, 2016).

⁴ Article 5 Group 1 baseline: Average production/consumption of HFCs in 2020–2022 + 65% of HCFCs baseline production/consumption; Article 5 Group 2 baseline: Average production/consumption of HFCs in 2024–2026 + 65% of HCFCs baseline production/consumption (The European FluoroCarbons Technical Committee), (UNEP, 2016).

instead of using empirical data. Additionally, we conduct a Monte Carlo simulation based on a pre-defined distribution of all model parameters (e.g., uniform, normal, triangular distribution) to address the scarce data challenge and increase the robustness of the results. Finally, it should also point out that our modeling is based on an eventual steady-state case where the cold chain is completely and evenly developed in China. In other words, all perishable products are stored and transported with appropriate refrigeration conditions rather than modeling the disparities in regions that have varying levels of cold chain development. These results suggest what the cold chain environmental impacts may be in the future after additional cold chain deployment.

2. Methods

2.1. System definition and functional unit

We consider the entire lifetime for food products from agricultural production to final consumption, focusing mostly on the post-agriculture supply chain where the cold chain is present. The functional unit is defined as 1 kg of edible food consumed in households and the GHG emission results are measured in kg of CO₂ equivalent per kg of food consumed [kg CO₂eq/kg consumption]. We assume agricultural activities include food production and processing (e.g., bone removing, peeling). As shown in Fig. 1, the post-agriculture cold chain includes refrigerated warehouse at the origins of production, 1st stage refrigerated transportation (long-distance), distribution center refrigerated storage at the places of sale, 2nd stage refrigerated transportation (short-distance), and retail stores. The household activities include household refrigeration, consumption, and food waste. In the system, we include the GHG emissions from refrigerant leakage, energy consumption associated emissions, and emissions due to food losses and wastes.

2.2. Cold chain scenarios

We defined eight cold chain scenarios in Table 1 to estimate GHG emissions and each scenario represents one food category at one storage condition. We considered four food categories, vegetables, fruit, meat, and aquatic products. Each food category is represented by typical food types (ST2, ST11 in the supplementary materials). We admit this generalization may introduce errors in the modeling. However, considering the scope of this paper is to present a robust emission estimation of using cold chain in China, it is reasonable to use the broad food categories. Similar generalized food categories are also used in the cold chain modeling by Hu et al. (Hu et al., 2019) and Heard et al. (Heard and Miller, 2018).

Additionally, we defined appropriate temperature levels in each scenario for the specific category: low-temperature (LT), medium-temperature (MT), and high-temperature (HT) according to the optimal storage temperature (Mercier et al., 2017). For instance, apple and orange belong to the MT fruit scenario, and banana belongs to the HT fruit scenario (Mercier et al., 2017). The detailed definition, value, and distribution of each parameter in all scenarios can be found in the Supplementary Materials.

2.3. Food losses modeling

Food losses refer to the decrease of food quantity or quality throughout the food supply chain which is essentially due to the growth of organisms and biochemical reactions or mishandling (Hu et al., 2019), (Hammond et al., 2015), (Food and Agriculture Organization of the United Nation). In this paper, we consider food processing (e.g., bone removal, peeling) as a part of agricultural activities and we assume the food products entering the cold chain are edible quantities. We assume the edible proportion is 60% for meat and aquatic products (Hamerschlag and Venkat, 2011) and 80% for vegetables and fruits (Hamerschlag and Venkat, 2011). Hence, the food quantity after harvesting is multiplied by the edible proportion to calculate the quantity entering the post-agriculture cold chain. During the post-agriculture cold chain (from the refrigerated warehouse to household refrigerator stages in Fig. 1), we referred to (Hoang et al., 2016), (Van Boekel, 2008) and regarded the food losses are merely due to the generic food quality (e.g., color, moisture, nutrition) degradation without other weighted losses.

The food quality degradation is described by the kinetic model and shown in Eq. (1) (Wu et al., 2019), (Van Boekel, 2008), (Rong et al., 2011). Q refers to food quality, k is the reaction rate, and n represents the reaction order. Using the kinetic modeling for food losses, we can emphasize the impacts of storage temperature. It has been found that the linear zero-order reaction ($n = 0$) and exponential first-order reaction ($n = 1$) are good fits for food quality evolution, which are showing in Eqs. (2) and (3), respectively (Rong et al., 2011; Li et al., 2020; Ling et al., 2015) – (Rong et al., 2011; Li et al., 2020; Ling et al., 2015). In Eqs. (2) and (3), Q_0 represents the initial food quality and t refers to the reaction time.

$$\frac{dQ}{dt} = kQ^n \quad (1)$$

$$Q = Q_0 - kt \quad (2)$$

$$Q = Q_0 e^{-kt} \quad (3)$$

The reaction rate k is mostly influenced by temperature and it is

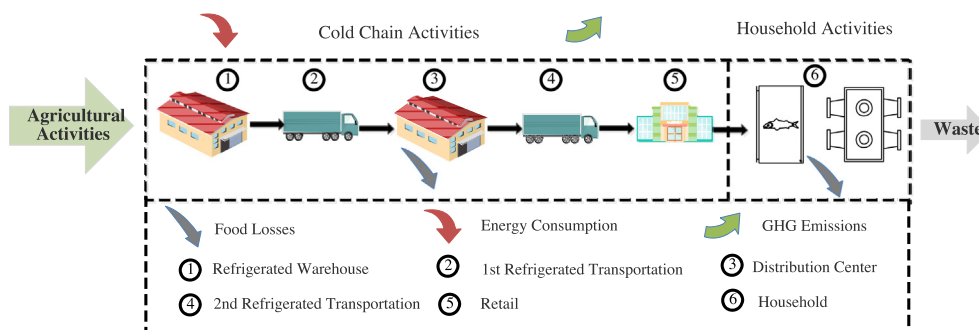


Fig. 1. The lifecycle of food product and cold chain system boundary. The complete lifecycle of perishable food product starts from agriculture activities and then is delivered through cold chain logistics. The post-agriculture activities are focused in the paper.

Table 1

Cold chain scenarios considered in this study. The category is according to the optimal storage temperature of each product.

Scenario	Storage type	Optimal storage temperature	Temperature in this study
HT vegetable	fresh	6°C to 12°C	8°C
HT fruit	fresh	6°C to 12°C	8°C
MT vegetable	fresh	0°C to 5°C	2°C
MT fruit	fresh	0°C to 5°C	2°C
MT meat	chilled	−2°C to 0°C	−2°C
MT aquatic	chilled	−2°C to 0°C	−2°C
LT meat	frozen	< −18°C	−22°C
LT aquatic	frozen	< −18°C	−22°C

widely modeled by the Arrhenius equation as a function of temperature (Van Boekel, 2008), (Rong et al., 2011), (Ling et al., 2015), (Mizrahi, 2011). As shown in Eq. (4), $k(T)$ is the reaction rate at temperature T (in K), k_0 is a constant, E_a is the activation energy, and R is the universal gas constant. As k_0 and E_a are temperature independent, the $k(T)$ can be estimated from a known reaction rate at the reference temperature (Van Boekel, 2008), (Mizrahi, 2011).

$$k(T) = k_0 e^{-\frac{E_a}{RT}} \quad (4)$$

Additionally, existing studies further simplified the method where the constant k_0 is avoided and the variable Q_{10} is introduced. As shown in Eq. (5), Q_{10} essentially means the ratio between the reaction rate at temperature $T + 10$ and that at temperature T (Wu et al., 2019), (Van Boekel, 2008), (Mizrahi, 2011). According to the Van't Hoff's rule, Q_{10} is between 2 and 3 at 0 to 10°C temperature range (Wu et al., 2019), (United States Department of Agriculture, 2016). In this study, we assume the Q_{10} is 2 for vegetables and fruit, while the Q_{10} is 2.5 for meat and aquatic.

$$Q_{10} = \frac{k_{T+10}}{k_T} \quad (5)$$

Thus, the food quality evolution can be modeled for the targeted food product at a specific temperature. In this study, we refer to Rong et al. (Rong et al., 2011) and assume the zero-order reaction for vegetables and fruit, while we consider a mixture of zero and first-order reaction for meat and aquatic according to Ling et al. (Ling et al., 2015). The reduction is considered as the first-order in the initial 3 h and zero-order otherwise because the reaction rate is faster during the cooling down process but will be slower afterward. According to the temperature level for each scenario defined in Table 1, we assume the product lifetime in each scenario (ST5) (Wu et al., 2019), (Vasavada, 1996), (Cantwell). We then computed the quality evolution based on the kinetic model and present the food losses curve for the post-agriculture stages of all scenarios in Fig. 2. Thus, the food losses in each can be estimated given the residence time in the cold chain.

As we define the functional unit as 1 kg of edible food consumed, the food losses and food quantity entering each cold chain stage are calculated back based on the food loss rate and storage time. The use of the kinetic model likely results in an underestimate of overall food losses, since it does not account for consumer preferences or behavior. The food quantity entering each previous stage can be calculated by the sum of food quantity entering the current stage and food losses at the previous stage. For instance, if the current cold chain stage is the 1st refrigerated transportation, the food quantity entering the previous stage, refrigerated warehouse, can be calculated by Eq. (6) and the food losses at the refrigerated warehouse are calculated from Eq. (7).

$$Q_{RW} = Q_{Trans1} + Q_{loss, RW} \quad (6)$$

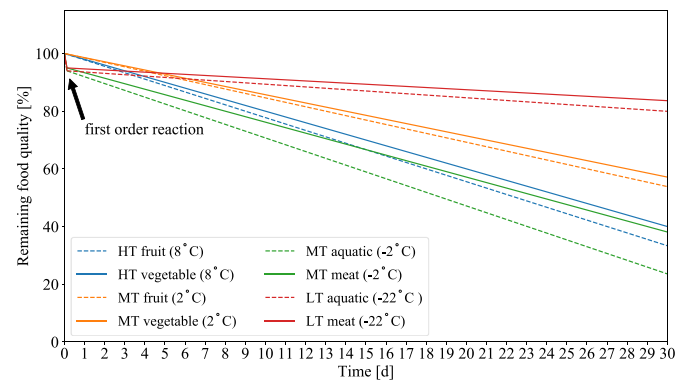


Fig. 2. Perishable product quality evolution. Fruit and vegetables follow zero order reaction. Aquatic and meat follow the mixed zero-first order reaction. Based on the reference quality evolution curve, the food losses for each product at any given temperature can be estimated.

$$Q_{loss, RW} = t_{RW} \times R_{Loss} \quad (7)$$

2.4. Simulation method

The paper estimates GHG emissions associated with the cold chain for vegetables, fruit, meat, and aquatic product in China. To take into account various sources of variability and uncertainty, Monte Carlo simulation is conducted of variables to enhance the robustness of results. We use the programming language Python3 to perform the Monte Carlo simulation and we run the model 10,000 times with randomly generated parameters every time. The lifecycle emissions are the summation of emissions at each stage defined in Section 2.5. Table 2 lists the definition of each parameter and the details regarding the specific parameter distribution and data sources are in ST1 in Supplementary Materials. Additionally, a sensitivity analysis is conducted to determine the degree of influence of each parameter (in Table 2) on the final results, using one-at-a-time perturbation. All parameters are fixed at their median value except the targeted parameter which is increased by 20% from its median.

2.5. Lifecycle inventory

2.5.1. Agricultural activities

The cradle-to-gate emission factors for agricultural activities of vegetables, fruit, meat, and aquatic products are obtained from existing studies. Porter et al. (Porter et al., 2016) studied the emission factors for industrialized Asia and Hamerschlag (Hamerschlag and Venkat, 2011) calculated the cradle-to-gate emissions factors. To characterize food emission factors (C_{food}) for China, we primarily use the industrialized Asia data from

Table 2

Parameters definition. See ST1 in Supplementary Materials for the value and distribution of each parameter.

Parameter	Definition	Note
C_{food}	Food production emission factors	The cradle-to-gate emissions of food. Specified for each food category
C_{pack}	Packaging emission factors	Calculated from food-to-packaging ratio. Specified for each food category
C_{Trans}	Specific emission of refrigerated transportation	GHG emissions without refrigerant leakage. Used in both transportation stages
D_1, D_2	Food mile of the 1st and 2nd refrigerated transportation	The food mile of the 1st stage is specified for each food category but not specified in the 2nd stage
E_{RW}, E_{DC}	Electricity consumption of refrigerated warehouse and distribution center	Specified for storage temperature
$E_{Retail,Ref}$	Refrigeration electricity consumption of retailing stores	Specified for food category and storage temperature
$E_{Retail,other}$	All other energy consumption of retailing stores	Specified for food category.
E_{House}	Household fridge electricity consumption	—
Em_{ele}	weighted lifecycle power generation emissions	Constant value. Calculated from the current power sources in China.
GWP_{leak}	Global warming potential of refrigerant Refrigerant leakage	Specified for different cold chain stages and refrigeration temperature Specified for each cold chain stage. For example, $leak_{RW}$ refers to the leakage at the refrigerated warehouse stage
R_{waste}	Food waste rate	Specified for each food category
t	Time spend at each cold chain stage	Specified for food category, cold chain stage, and refrigeration temperature. For instance, t_{RW} refers to the time stored at the refrigerate warehouse
v_1, v_2	Truck speed at the 1st and 2nd refrigerated transportation	—
Q_{loss}	Food losses	Calculated for each cold chain stage and specified for each food category. For example, $Q_{loss, RW}$ is the food losses at the refrigerated warehouse
Q_{waste}	Food waste at the end of consumption	Specified for each food category
$Q_{RW}, Q_{DC}, Q_{Trans1}, Q_{Trans2}, Q_{Retail}, Q_{House}$	Food quantity entering each stage	Calculated back based on one kg food consumed Q_{loss} , and Q_{waste} .
Em	GHG emission	Calculated at each cold chain stage and for each food category. Specified for emission sources. For instance, $Em_{leak, RW}$ is the calculated GHG emissions from refrigerant leakage at the refrigerated warehouse

(Hamerschlag and Venkat, 2011) and supplement not present data in (Porter et al., 2016). The original data source is summarized in the ST2 in the Supplementary Materials. The C_{food} taken from (Porter et al., 2016) are primarily US-based and we converted it to model China by the difference of agriculture production emission intensity between the US and China (ST3). Notice that the emission factors are also used to calculate the food loss emissions at each cold chain stage, as we follow the definition of Hu et al. (Hu et al., 2019) considering that the food loss emissions result from the waste of invested carbon in agricultural activities.

2.5.2. Refrigerated warehouse

The refrigerated warehouse mainly involves precooling and refrigerated storage. In our paper, we assume all food products use warehouse precooling because it is the most used approach in China (Zhao et al., 2018). Hence, the energy consumption of the precooling process is included in the refrigerated storage energy consumption. Besides, we add the packaging emissions in the refrigerated warehouse stage. Note that packaging emissions are not refrigeration related, and we simply consider it at the beginning of the cold chain. We refer to the study by Heller (Heller et al., 2019) and consider the packaging emission factor (C_{pack}) is proportional to C_{food} by the coefficient food to packaging ratio (FTP). In other words, C_{pack} equals C_{food} divided by FTP. The original data for FTP is shown in ST6 in the Supplementary Materials.

$$Em_{pack, RW} = Q_{RW} \times C_{pack} \quad (8)$$

The GHG emissions of refrigerated storage are allocated to refrigerant leakage, energy consumption, and food losses. Regarding refrigerant leakage, we consider a 20-year equipment lifetime with 8% annual operational leakage, 1% of installation leakage, and 5% disposal leakage (Hoang et al., 2016), (United

Nations Environment Programme, 2018). Firstly, the annual leakage rate is multiplied with the initial refrigeration charge of a commercial refrigerated warehouse (2000–10,000 kg) and then divided by the annual throughput product quantity (approximately six times of warehouse capacity) (United Nations Environment Programme, 2018), (China Federation of Logistics & Purchasing (CFLP), 2018). Secondly, the installation and disposal leakage are divided by the lifetime throughput product quantity. The refrigerant leakage allocated to one kg food product in 1 h ($leak_{RW}$) is the sum of both leakages over each associated time spent. We then calculate the direct GHG emissions ($Em_{leak, RW}$) by Eq. (9) where t_{RW} is the storage time and GWP is the mean of the most used refrigerant in China (R22, R404a, and R134a) (Zhao et al., 2018), (Zhang et al., 2019a). See ST7 in Supplementary materials for detailed data refrigerant leakage allocation.

$$Em_{leak, RW} = leak_{RW} \times GWP \times Q_{RW} \times t_{RW} \quad (9)$$

The cclcn.com reports the daily electricity consumption for different capacities of refrigerated warehouse in China (cclcn.com, 2012). We assume a 10-h compressor operating time and food products load 75% of refrigerated warehouse capacity on average. Thus, the daily electricity consumption data is divided by 75% of warehouse capacity and then divided by 10 to reach the electricity consumption for one ton product in 1 h (E_{RW}). Eq. (10) calculates the GHG emissions from electricity consumption of refrigerated warehouse ($Em_{ele, RW}$) where Em_{ele} [gCO₂e/kWh] refers to the weighted lifecycle power generation emissions in China. Em_{ele} is calculated from the Chinese electricity generation structures and emissions of each power source (Li et al., 2017), (International Energy Agency (IEA)b). See ST8 and ST9 in Supplementary Materials for daily refrigerated warehouse electricity consumption and power source in China.

$$Em_{ele, RW} = E_{RW} \times Em_{ele} \times Q_{RW} \times t_{RW} \quad (10)$$

Eq. (11) calculates the food losses emissions ($Em_{loss, RW}$) which is multiplied from food losses quantity at refrigerated warehouse ($Q_{loss, RW}$) and losses emission factors (C_{loss})

$$Em_{loss, RW} = Q_{loss, RW} \times C_{loss} \quad (11)$$

2.5.3. 1st refrigerated transportation

The 1st stage transportation is the long-distance truck refrigerated transportation from the origins of production to distribution centers. We assume an 8% annual refrigerant leakage rate and multiply it with the refrigerant charge quantity (3–8 kg); then divided the value by the annual truck travel distance (assume 60,000 km in China) and truck capacity (3–11 ton) to allocate the refrigerant leakage to one kg food product per km travelled ($leak_{Trans}$) (United Nations Environment Programme, 2018), (Tassou et al., 2009). The food miles of big cities in China are studied by Huang et al. (Huang et al., 2014), which provides data for the 1st stage travel distance (D_1) of each food category. Thus, the GHG emissions associated with leakage ($Em_{leak, Trans}$) can be calculated by Eq. (12) where Q_{Trans1} is the food quantity entering this stage and GWP is the mean value of the most used refrigerant (R134a/R404a). Original data source is in ST7 in Supplementary Materials.

$$Em_{leak, Trans1} = leak_{Trans} \times GWP \times Q_{Trans1} \times D_1 \quad (12)$$

We refer to a UK based study (Tassou et al., 2009) for the fuel efficiency [mL/ton-km] of refrigerated vehicles. The fuel efficiency is assumed to be the same in the UK and China. Then, we use an emissions factor of refrigerated vehicles in China (2.63 kgCO₂/L) (Liu et al., 2020) to compute the specific emissions of refrigerated transportation (C_{Trans}) measured in gram of CO₂ equivalent per ton product per km travelled. The compiling of C_{Trans} can be found in ST 4 in the supplementary materials. Eq. (13) calculates the energy usage related GHG emissions with specific refrigeration temperature conditions.

$$Em_{e, Trans1} = C_{Trans} \times Q_{Trans1} \times D_1 \quad (13)$$

As we define the food losses is a function of time (Section 2.3), we use D_1 divided by the truck speed (v_1) to reach the time spent during the 1st transportation stage where the speed limit for trucks on expressways in China is 80–100 km/h (Road Traffic Safety Law o, 2011). Thus, the food losses in the 1st refrigerated transportation stage ($Q_{loss, Trans1}$) are calculated and food loss emissions can be calculated by Eq. (14).

$$Em_{loss, Trans} = Q_{loss, Trans1} \times C_{loss} \quad (14)$$

2.5.4. Distribution center

The calculation method for the distribution center stage is the same as the refrigerated storage process in the refrigerated warehouse stage. Eq. 15–17 calculate the GHG emissions from refrigerant leakage, electricity consumption, and food losses where t_{DC} differentiates the refrigerated warehouse stage and the distribution center stage.

$$Em_{leak, DC} = leak_{DC} \times GWP \times Q_{DC} \times t_{DC} \quad (15)$$

$$Em_{ele, DC} = E_{DC} \times Em_{ele} \times Q_{DC} \times t_{DC} \quad (16)$$

$$Em_{loss, DC} = Q_{loss, DC} \times C_{loss} \quad (17)$$

2.5.5. 2nd refrigerated transportation

The 2nd stage, short-distance refrigerated transportation from distribution centers to local markets. We use the same approach in Section 2.5.3 to calculate the GHG emissions from the 2nd refrigerated transportation with travel distance (D_2) and truck speed (v_2) differentiate both steps.

$$Em_{leak, Trans2} = leak_{Trans} \times GWP \times Q_{Trans2} \times D_2 \quad (18)$$

$$Em_{e, Trans2} = C_{Trans} \times Q_{Trans2} \times D_2 \quad (19)$$

$$Em_{loss, Tran2} = Q_{loss, Trans2} \times C_{loss} \quad (20)$$

2.5.6. Retail

Refrigerant leakage at retailing stores ($leak_{Retail}$) is assumed to be the same as $leak_{RW}$ ($leak_{DC}$). The leakage emissions ($Em_{leak, Retail}$) can therefore be calculated by Eq. (21) where Q_{Retail} is the food quantity entering the retail stage and t_{Retail} refers to the time duration in this stage. See ST7 in Supplementary Materials for details refrigerant leakage allocation and refrigerant assumptions.

$$Em_{leak, Retail} = leak_{Retail} \times GWP \times Q_{Retail} \times t_{Retail} \quad (21)$$

The electricity consumption in the retail stage are divided into refrigeration electricity consumptions ($E_{Retail, ref}$) and all other energy consumptions ($E_{Retail, other}$) (Heller et al., 2019). We calculate the $E_{Retail, ref}$ from the energy usage of display cases where we assume closed cases are used for LT applications while open cases are used for HT/MT products. According to Fricke and Becker (Fricke and Becker, 2011), the energy consumption of open and closed display cases is 56 and 40 kWh/day per case and we convert it to kWh/day per cubic meter based on the case size (considering 75% full of total capacity). Then, the data is divided by the food bulk density and 24 to reach kWh/ton-h. See the ST10 for display case parameters and ST11 for the food bulk density in Supplementary Materials (Charrondiere et al., 2012).

We use the economic data of the retail sector in China (ST12 in Supplementary Materials) to allocate the $E_{Retail, other}$. The annual sales revenue in China in 2018 of vegetables, fruit, meat, and aquatic are divided by the total revenue of the retail sector (National Bureau of Statistics of China). Afterward, the ratio is multiplied with the total energy consumption of the retail sector in 2018, and then divided by the consumed food quantity of each product to calculate $E_{Retail, other}$ (National Bureau of Statistics of China). Hence, the energy consumption related emissions ($Em_{ele, Retail}$) can be calculated by Eq. (22) where Q_{Retail} is the food quantity entering retailing stores and t_{Retail} refers to the storage time in the retail stage.

$$Em_{ele, Retail} = (E_{Retail, ref} + E_{Retail, other}) \times Em_{ele} \times Q_{Retail} \times t_{Retail} \quad (22)$$

Eq. (23) calculates the food losses emissions ($Em_{loss, Retail}$) by the multiplication of the quantity of food losses at retailing stores ($Q_{loss, Retail}$) and losses emission factors (C_{loss})

$$Em_{loss, Retail} = Q_{loss, Retail} \times C_{loss} \quad (23)$$

2.5.7. Household

The calculation of the domestic fridge storage is the same as previous cold storage stages as shown in Eq. (24) and Eq. (25). Note that the annual leakage rate is merely 0.3% of household refrigerators, so it is neglected (United Nations Environment Programme, 2018).

$$Em_{ele, House} = E_{House} \times Em_{ele} \times Q_{House} \times t_{House} \quad (24)$$

$$Em_{loss, House} = Q_{loss, House} \times C_{loss} \quad (25)$$

Food wastes are generated during household storage and the food waste quantity is calculated by Eq. (26) where R_{Waste} refers to the food waste rate. Blakeney from the Food and Agriculture Organization of the United Nations (FAO) recorded the food waste rate for industrialized Asia, which is used to model the food waste in China (Blakeney, 2019). The emissions associated with food losses (Em_{Waste}) can be calculated by Eq. (27).

$$Q_{Waste} = \frac{1}{(1 - R_{Waste})} \times R_{Waste} \quad (26)$$

$$Em_{Waste} = Q_{Waste} \times C_{loss} \quad (27)$$

Thus, the lifecycle GHG emissions of each scenario defined in Table 1 can be calculated by accumulating the emissions of each stage from Section 2.5.1 to Section 2.5.7. The definition of all parameters in our modeling is listed in Table 2 and the details of data descriptions can be found in ST1 in Supplementary materials. It is worth noting that it is challenging to use China-specific data for all parameters due to data availability. In Table 2, D_1 , D_2 , v_1 , v_2 , E_{RW} , E_{DC} , $E_{Retail, other}$, Em_{ele} , GWP , and R_{Waste} are specified for China. Meanwhile, C_{food} combines the food losses emissions in the US and industrialized Asia; however, the data from the US is converted by a coefficient to model China (ST3). Besides, to compile C_{Trans} (ST4), we assume the fuel efficiency of refrigerated vehicles are the same in the UK and China (Tassou et al., 2009); however, the fuel emission factor is from a China-based study (Liu et al., 2020). Overall, most parameters are China-specific and non-China data are also corrected; hence, the results of our study can still robustly indicate the cold chain emissions in China.

3. Results

3.1. Food lifecycle GHG emissions

We first calculate the lifetime GHG emissions of each scenario defined in Table 1. The lifetime GHG emissions include the cradle-to-gate agriculture production emissions, post-agriculture cold chain, and household emissions. We report the median emissions of 10,000 times of Monte Carlo simulation and divide them into three main stages (agriculture, cold chain, and household). The results are shown in Fig. 3, with Fig. 3a illustrating the absolute values and Fig. 3b showing the contributions in percentage.

The most apparent character is the difference in GHG emissions between meat/aquatic and vegetable/fruit scenarios. As expected (Clune et al., 2017), the lifecycle GHG emissions of meat and aquatic products are much higher than fruit and vegetable products in China. On average, four meat/aquatic scenarios generate 15.6 kg CO₂eq/kg consumption more than vegetable/fruit scenarios. In meat/aquatic scenarios, cradle-to-gate agriculture activities contribute to a significant portion. 74% (8.2 kg CO₂eq/kg consumption) and 83% (21.0 kg CO₂eq/kg consumption) of GHG emissions in LT aquatic and LT meat scenarios are from agriculture activities. Similarly, agriculture emissions contribute to 84% (7.7 kg

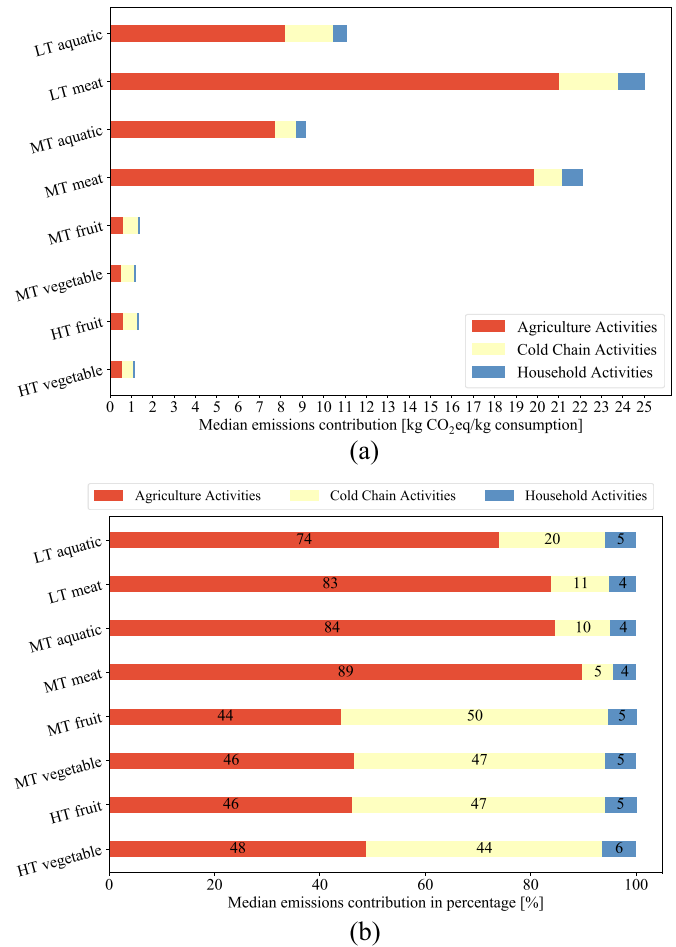


Fig. 3. Lifetime GHG emissions (median value) breakdown into three parts (agriculture, cold chain, and household activities).

CO₂eq/kg consumption) and 89% (19.8 kg CO₂eq/kg consumption) in the MT meat and MT aquatic scenarios. In the vegetable/fruit scenarios, agriculture activities and cold chain activities contribute to an approximately equal amount of GHG emissions (~47%), while the emissions from household activities are around 5%.

It is not surprising that the cradle-to-gate agriculture activities constitute for a large portions as it includes raw materials production (e.g., fertilizer), waste management (e.g., on-farm manures), on-farm energy use, and raw materials transportation at the agriculture stage (Hamerschlag and Venkat, 2011), (Porter et al., 2016). Besides, we consider the processing (e.g., bone removing, peeling) as a part of agriculture activities in this paper, which also generate GHG emissions. Several studies (Hoang et al., 2016), (Heard et al., 2019), (Hamerschlag and Venkat, 2011) also showed that food production contributes to a significant proportion of total GHG emission. For instance (Hamerschlag and Venkat, 2011), found nearly 90% of lamb lifetime GHG emissions are in the production phase.

In China, the cradle-to-grave food lifetime emissions are rarely studied, especially when using cold chain logistics. Our following results present an early estimation of the entire lifecycle GHG emissions for food products in China and the higher resolution calculations of post-agriculture emissions allow greater analysis of the environmental impacts of the cold chain.

3.2. Post-agriculture GHG emissions

This paper focuses on the post-agriculture GHG emissions to better analyze the contributions of the cold chain. Results of the Monte Carlo simulation are given in Fig. 4. Unless otherwise indicated, all values reported are the median value of the 10,000 simulations. The first observation from Fig. 4 is that the eight scenarios can be divided into two groups (vegetable/fruit and meat/aquatic) based on the emission level. Even when agricultural production is not taken into account, the post-agriculture emissions from meat/aquatic products are still significantly higher than those of vegetables and fruit. On average, the median emissions of LT/MT meat scenarios are 0.9 kg CO₂eq/kg consumption higher than that of LT/MT aquatic scenarios and 2.4 kg CO₂eq/kg consumption higher than that of four vegetable/fruit scenarios. The significant emission differences across eight scenarios mainly result from food losses, which are a function of (C_{food}) of different food categories (Hu et al., 2019). Meat products have the most embodied carbon associated with their production; therefore, even when the loss quantity of meat is the same as vegetable or fruit, its associated GHG emissions are amplified by C_{food} .

The median emissions of LT/MT meat scenarios are 4.0 and 2.2 kg CO₂eq/kg consumption, and ranging from 0.8 to 8.3 kg CO₂eq/kg consumption. The C_{food} for producing one kg poultry, pork, and beef are 3, 6, and 18 kg CO₂eq, which makes significant emissions variations in meat (Hamerschlag and Venkat, 2011), (Porter et al., 2016). Moreover, a median of 2.8 and 1.4 kg CO₂eq emissions are generated from LT/MT aquatic scenarios. The range of lifecycle emissions of aquatic products is 0.8–4.0 kg CO₂eq/kg consumption which is much smaller than that of meat products. Regarding vegetables and fruit, the median emissions of HT and MT fruit (0.73 and 0.77 kg CO₂eq/kg consumption) are slightly higher than that of HT/MT vegetable scenarios (0.60 and 0.64 kg CO₂eq/kg consumption). Over 80% of the Monte Carlo simulation results of HT fruit (and MT fruit) are higher than the median emissions of HT vegetable (and MT vegetable). The main reason is that the fruit loss rate is larger than the vegetable loss rate during the cold chain. As a result, emissions associated with fruit losses are larger than that of vegetable losses leading to more lifecycle emissions.

Fig. 4 also indicates that lower temperature conditions tend to have higher total GHG emissions. Comparing LT and MT meat scenarios, the LT meat scenario has 1.7 kg CO₂eq/kg consumption more emissions than the MT meat scenario. The deciding reason is again food losses related emissions. Although the meat and aquatic loss rate in LT conditions (−22°C) is merely 20% of that in MT

conditions (−2°C), the frozen meat and aquatic products spent around 900 h (~37 days) more than chilled meat and aquatic products in refrigerated storage facilities. Our modeling results show that the quantity of FLW in the LT meat scenario is larger than that of the MT meat scenario by 0.05 kg due to the long residence time. Besides, the energy usage related emissions of the LT meat scenario at the refrigerated warehouse, distribution center, and two distribution stages are higher than that of the MT meat scenario, while the energy emission at retailing stores of LT meat is lower than the MT meat because closed display cases used for LT products are more energy-efficient than open cases for MT cases. Hence, combining the impacts of residence time and energy consumption, the LT meat scenario generates 1.7 kg CO₂eq/kg consumption more than the MT meat scenario. Due to the same reason, the total GHG emissions of the LT aquatic scenario is 1.5 kg CO₂eq/kg consumption more than the MT aquatic scenario. However, the emission difference between HT/MT vegetable scenarios (also HT/MT fruit scenarios) is not significant with merely around 0.04 kg CO₂eq more in MT conditions on average. It is because the cold chain residence time of MT vegetable/fruit is merely 12 h longer than HT vegetable/fruit.

We also divide the post-agriculture GHG emissions into six stages (Fig. 5) with Fig. 5a showing the absolute emissions and Fig. 5b illustrating the emissions contribution in percentage. As we discussed before, the food emissions factor (C_{food}) amplified the GHG emissions due to FLW in meat/aquatic scenarios.

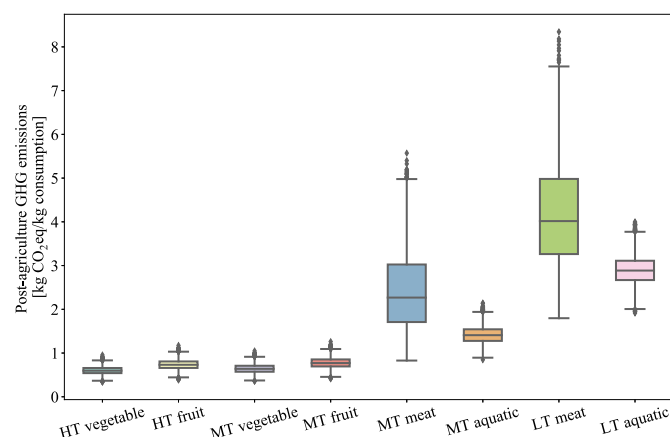
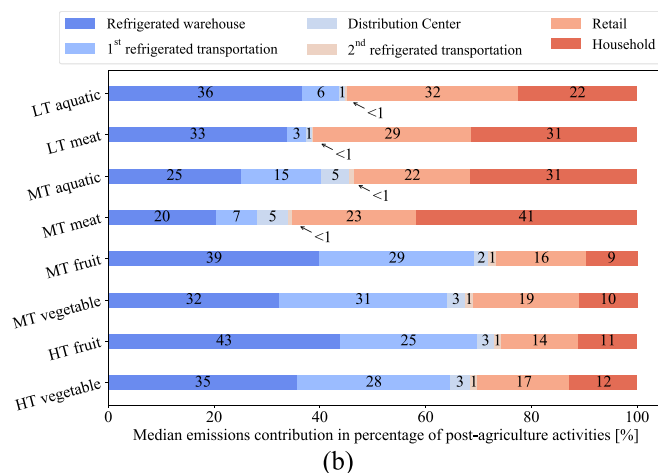
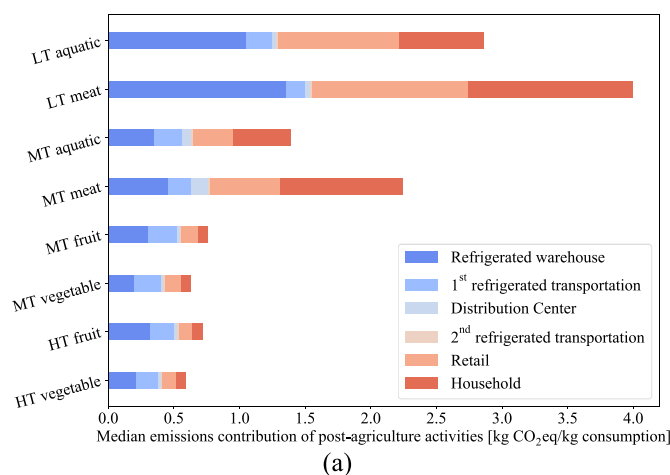


Fig. 4. Post-agriculture GHG emission including emissions cold chain activities and household activities.

Fig. 5. Median GHG emission breakdown into five cold chain stages and household activities post-agriculture emissions).

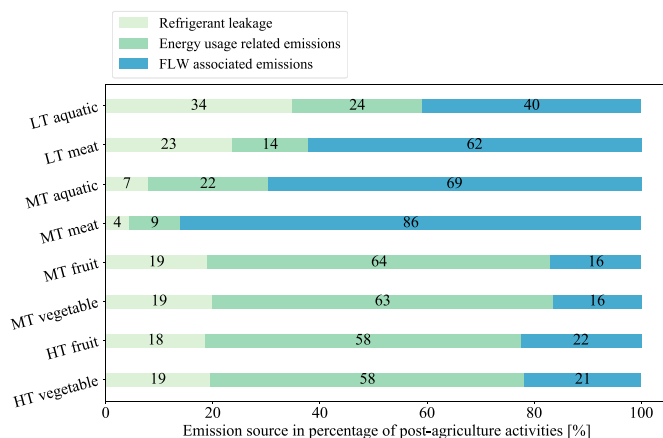


Fig. 6. GHG emissions breakdown into refrigerant leakage, energy consumption, and FLW associate emissions for refrigeration related stages (post-agriculture emissions).

Comparing emissions from each cold chain stage, Fig. 5 shows that the aquatic/meat and vegetable/fruit scenarios have different features. In the LT aquatic scenario, refrigerated warehouse, retail, and household are the largest three emission contributors accounting for 36% (1.1 kg CO₂eq/kg consumption), 32% (0.9 kg CO₂eq/kg consumption), and 22% (0.6 kg CO₂eq/kg consumption), respectively. Those three stages also produce the largest emission in the LT meat scenario with 33% (1.3 kg CO₂eq/kg consumption), 29% (1.19 kg CO₂eq/kg consumption), and 31% (1.25 kg CO₂eq/kg consumption) for each. In the MT meat and MT aquatic scenarios, the contribution of GHG emissions from household activities increases to 41% (0.9 kg CO₂eq/kg consumption) and 31% (0.5 kg CO₂eq/kg consumption), respectively. The absolute GHG emissions from the refrigerated warehouse in the MT meat (0.4 kg CO₂eq/kg consumption) and MT aquatic (0.3 kg CO₂eq/kg consumption) scenarios have decreased compared with that in LT conditions due to shorter residence time. However, the wastes of meat and aquatic embodied emissions do not change significantly leading the household stage to be the most emissions contributor. In comparison, the emissions from the refrigerated warehouse and 1st refrigerated transportation constitute the largest proportion in vegetable/fruit scenarios. On average, refrigerated warehouse and 1st refrigerated transportation account for 37% (0.26 kg CO₂eq) and 28% (0.19 kg CO₂eq) in MT/HT vegetable scenarios. Comparing vegetables and fruit, the emissions of both fruit scenarios are slightly larger than that of vegetable scenarios. It is because more embodied emissions are generated in agriculture activities for fruit; hence the FLW associated emissions of fruit scenarios will be higher than that of vegetables.

To analyze the source of GHG emissions, we break down the post-agriculture GHG emissions into refrigerant leakage, energy consumption, and FLW associated emissions. As Fig. 6 displays, the majority of emissions in fruit/vegetable scenarios are from energy usage related emissions, while FLW associated emissions represent a considerable number of emission in meat/aquatic scenarios.

Firstly, 61% (0.28 kg CO₂eq/kg consumption) of emissions on average are energy consumption related emissions in the four vegetable/fruit scenarios. The emissions from energy usage of vegetables and fruit in MT conditions are slightly higher than that in HT conditions (by around 0.05 kg CO₂eq/kg consumption), which is mainly because that more energy is consumed to reach the MT conditions (2 °C) than the HT conditions (8 °C). The refrigerant leakage and FLW emissions in vegetable/fruit scenarios share a similar proportion (~19%). When it comes to aquatic/meat scenarios, the largest emissions contributor becomes FLW associate

emissions. In the MT meat scenario, 86% of emissions (1.7 kg CO₂eq/kg consumption) are made up of FLW emissions, and this number decreases to 62% (2.3 kg CO₂eq/kg consumption) in the LT meat scenario. Similarly, the proportion of FLW emissions in the MT aquatic scenario is 69% (0.8 kg CO₂eq/kg consumption) and it decreases to 40% (1.1 kg CO₂eq/kg consumption) in the LT aquatic scenario. Noted that the absolute emissions from FLW increase from MT to LT conditions in aquatic/meat scenarios. The percentage decrease comes from the gained refrigerant leakage and energy usage related emissions due to the much longer storage time and slightly increased energy consumption in LT conditions. The FLW associated emissions are calculated by multiplying C_{food} and FLW quantity. Considering the high C_{food} value for meat and aquatic products, the FLW emissions in meat/aquatic scenarios could be augmented small quantity of FLW.

3.3. Sensitivity analysis

We conduct sensitivity analysis to determine how variability and uncertainty of the model parameters impact the results of GHG emissions. Additionally, the results of sensitivity analysis also potentially imply approaches to reduce GHG emissions. It again should be noticed that the sensitivity analysis is conducted from post-agriculture stages, due to the overall focus on cold chain related activities.

In this study, we reduce the value of one parameter by 20% at each simulation run while keeping all other parameters constant at their median. The results of sensitivity analysis are shown in the heat map (Fig. 7), with Fig. 7a displaying the emission changes in absolute value and Fig. 7b illustrating the emission changes in percentage. Overall, the visible variation in magnitude in Fig. 7 suggests that C_{food} and t (time spent at each stage) are the most influential parameters in this study. Generally, reducing C_{food} leads to considerable changes in all scenarios. At least 0.22 kg CO₂eq/kg consumption (7.4%) and 0.015 kg CO₂eq/kg consumption (2.2%) emission reduction can be achieved in meat/aquatic and vegetable/fruit scenarios by decreasing the C_{food} . The largest emission reduction is 0.47 kg CO₂eq/kg consumption in the LT meat scenario. Moreover, time spent in cold chain facilities (t_{RW} , t_{DC} , t_{Retail} , and t_{House}) also have strong influences on the emissions. The longer time the product is stored, the more embodied emissions the product would have. For instance, reducing 20% of storage time in retailing stores would lead to 0.25 kg CO₂eq/kg consumption (6.3%) and 0.2 kg CO₂eq/kg consumption (7.1%) decrease in LT meat and LT aquatic scenarios, and the emissions of the other six scenarios also decrease by 4.2% on average. Besides, reducing C_{pack} could also decrease emissions especially in vegetable/fruit scenarios.

Significant emission reductions in absolute values are normally found in meat/aquatic scenarios, while the notable emission reductions in percentage are generally in vegetable/fruit scenarios. Taking the LT meat scenario and an example, $leak$, GWP , R_{waste} , and Em_{ele} are also crucial variables other than C_{food} and t . Parameters $leak$ and GWP are associated with direct emissions from refrigerant leakage. Reducing refrigerant leakage at the refrigerated warehouse by 20% can decrease 0.089 kg CO₂eq/kg consumption (2.2%), and more significantly, 0.18 kg CO₂eq/kg consumption (4.4%) can be decreased if a lower GWP refrigerant is used. Reducing the GHG emissions from the power grid (Em_{ele}) can reduce 0.079 kg CO₂eq GHG emissions (2%). Additionally, food waste is a substantial emission source; hence decreasing R_{waste} is helpful to reduce the emissions by 0.13 kg CO₂eq/kg consumption (3.2%). In the MT vegetable scenario, the parameters associated with the 1st refrigerated transportation (C_{Trans} and D_1) greatly contribute to GHG emissions besides of critical variables analyzed before. If C_{Trans} and D_1 are decreased, 0.04 kg CO₂eq/kg consumption (6.3%) and

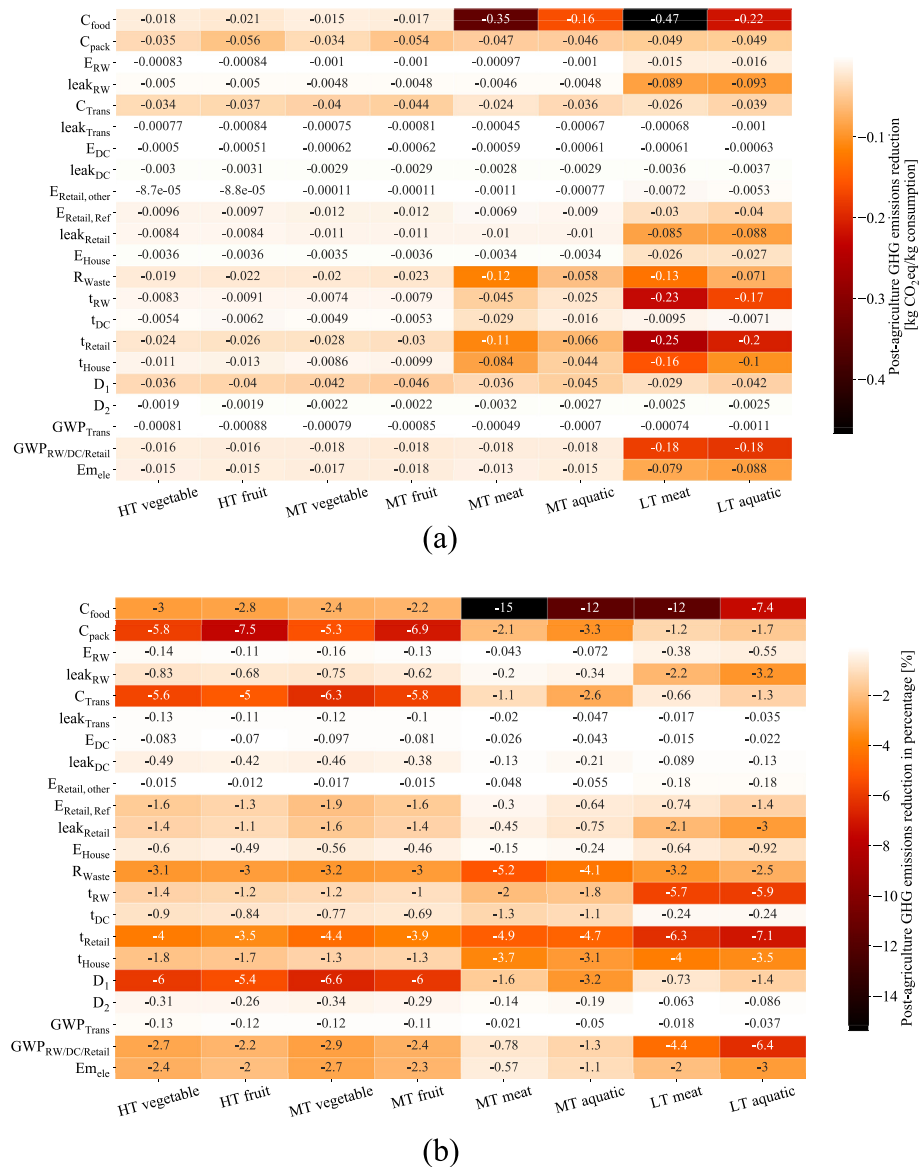


Fig. 7. The GHG emission changes (post-agriculture emissions) of sensitivity analysis. Keeping all other parameters at their median value while reducing the current targeted parameter by 20% from its median.

0.042 kg CO₂eq/kg consumption (6.6%) emission reduction can be achieved in the MT vegetable scenario.

4. Discussion

Based on our results of 1 kg consumed food product, we also approximate the aggregated lifecycle emissions at the national level in China. We multiply the consumption quantity of vegetables, fruit, meat, and aquatic in China in 2018 (ST12 in Supplementary Materials) with the 1 kg based lifecycle emissions of each food product. The estimation shows that if the cold chain were fully developed in China, the aggregated post-agriculture GHG emissions of the studied food category would be roughly in the range of 280–400 Mt CO₂eq. As a reference, the total CO₂ emissions of China is 10,064 Mt in 2018, and thus, the post-agriculture emissions of vegetables, fruit, meat, and aquatic account for approximately 3% of total emission in China based on the 2018's level (International

Energy Agency (IEA)a). The 3% of total emission in China is slightly higher than James's estimation that the food cold chain accounts for about 1% of carbon emission in the world (James and James, 2010). It should be noted that our result is based on the cold chain fully developed assumption. With the total GHG emissions in China being expected to grow in the coming years, it is reasonable to expect 1–3% of total GHG emissions to come from the food cold chain in China in the future. Li (Li et al., 2016) reported that over 10% of GHG emissions are from the food system in China; however, one should note that a dominant proportion is from agriculture activities. Hence, this paper conveys a key message in that, even though agricultural emissions dominate the environmental impacts of the food system, post-agriculture cold chain emissions are also significant on an absolute basis, and should not be obscured by a focus on agricultural emissions.

The results of the sensitivity analysis for post-agriculture emissions illuminate important measures that might be

undertaken for potential emission reduction. Above all, it is well understood that reducing food embodied emissions from agriculture activities is the most critical step to reduce the lifecycle emissions of food products. In the post-agriculture stages, it is important to reduce cold chain energy usage related emissions because it constitutes approximately 60% of total post-agriculture GHG emissions for vegetables and fruit (see Fig. 6). On one hand, emission reduction from electricity usage can be achieved either by improving the energy efficiency of refrigeration equipment or using renewable electricity sources. For instance, Wu concluded that if solar power is used, the emissions can be reduced by 8.5% (Wu et al., 2019). On the other hand, emissions from non-electricity energy usage, mainly from refrigerated vehicles, can be reduced by replacing diesel/gasoline with electric vehicles. In addition, reducing FLW is essential to decrease lifecycle emissions of meat and aquatic products (see Fig. 6). Due to the considerable embodied carbon from production, even a small quantity of FLW will lead to significant emissions. Beyond using refrigeration technologies to prevent food spoilage, it is more important for consumers to reduce food waste which is approximately 5%–10% of the initial production quantity in China (Blakeney, 2019). In this paper, we also highlight the impacts of food storage time of frozen meat/aquatic in cold chain facilities, especially in the refrigerated warehouse, 1st refrigerated transportation, and retailing stores. The longer the products are stored, the more emissions will be embodied in food products. Additionally, diminishing emissions from packaging and using cleaner refrigerants are effective approaches to reduce food lifecycle emissions.

We admit our study is not without flaws. Firstly, data quality is always a challenge in LCA studies, especially for an emerging industry (Miller and Keoleian, 2015). In this paper, 51 parameters are used in the model (ST1 in the supplementary materials). Although 40 parameters are China-specific or universal, the compiling of C_{food} and C_{Trans} partially referred to studies based on the US (Hamerschlag and Venkat, 2011) or the UK (Tassou et al., 2009). We made corrections for C_{food} and C_{Trans} to model China (ST3 and ST4), but undoubtedly, higher data quality can improve our study. Since most parameters are China-based, our results can still reveal a robust estimation of cold chain emissions in China. Secondly, our study reflects the future developed scenario but does not capture the transitions of the supply chain as it develops over time. One should note that the food supply chain structure is changing with the penetration of the cold chain in China. For instance, Garnett concluded that the food supply chain is lengthening in China (Garnett and Wilkes, 2014).

Additionally, the present paper, similar to other food LCA studies (Hoang et al., 2016), (Heard et al., 2019), represents a food product-oriented, cross-sector perspective of GHG emissions. However, one should properly understand that those studies estimate the coupled effects between perishable food products embedded emissions and cold chain facilities operation emissions. It does not reflect the lifetime emissions of the cold chain facilities themselves (i.e. the construction, operation, and retirement of refrigerated warehouses and refrigerated vehicles), which are interdependent with the food system and are not easily measured in terms of a standalone functional unit. Nevertheless, the impacts of cold chain infrastructure are not well understood and future studies are needed on the GHG emissions of the cold chain infrastructure to reveal the environmental impacts of the cold chain industry.

5. Conclusion

In this paper, we investigate the lifecycle GHG emissions of consuming 1 kg of unprocessed vegetables, fruit, meat, and aquatic products delivered by cold chain logistics in China, based on the

assumptions of a fully developed cold chain to approximate the total potential contribution of the cold chain industry to nationwide GHG emissions. In total, eight cold chain scenarios with each scenario representing one food category in one temperature condition (HT, MT, or LT) are considered in our study. We analyzed the total lifecycle GHG emissions in each cold chain scenario, breaking down emissions into different stages and sources, and conducting a one-at-a-time parameter sensitivity analysis. The main conclusions are drawn as follows:

- (i) Although agriculture activities dominate the environmental impacts along the food lifecycle, the GHG emissions of post-agriculture cold chain and household activities are still significant on an absolute basis and should not be overshadowed. The post-agriculture activities of food supply chains could potentially contribute to 1–3% of total emissions in China.
- (ii) In the post-agriculture stages, it is found that household, retail, and refrigerated warehouses are the largest three emission stages for meat/aquatic scenarios, while most of the emissions of fruit/vegetable scenarios are from the refrigerated warehouse and 1st refrigerated transportation stages. In the four vegetable/fruit scenarios, most of the emissions are from cold chain activities with an average of 54%.
- (iii) The energy usage of the cold chain (e.g., refrigeration, transportation) results in around 61% of post-agricultural emissions in fruit/vegetable scenarios, which suggests that using lower-carbon energy sources is an effective approach to reduce post-agriculture cold chain emissions of fruits and vegetables. In contrast, FLW emissions are the highest contributor to meat/aquatic post-agricultural emissions. It is because the FLW emissions are amplified by significant carbon invested in producing meat/aquatic products. Even a small quantity of food loss or waste could lead to considerable GHG emissions. Hence, using the cold chain to reduce food losses and changing behaviors to reduce food wastes are critical approaches.
- (iv) According to the observations of sensitivity analysis, decreasing the food losses and wastes and time duration spent in cold chain activities would have significant influences on the post-agriculture GHG emissions. Reduction of those factors, together with reducing refrigerant leakage, using lower-GWP refrigerants, and reducing emissions associated with transportation and electricity production can be effective to reduce the total lifecycle emissions of the food system. Such changes require improvement from multiple aspects across the supply chain including agriculture technologies, refrigeration technologies, and behaviors of managing food products.

The perishable food cold chain will inevitably develop significantly in the coming years in China due to economic growth and improvements in the standard of living. This paper presents an estimation of what lifecycle GHG emissions of perishable food cold chain would be expected after China has a fully developed food cold chain if significant interventions are not enacted. Essentially, by understanding the GHG emissions at each stage of the food lifetime, decisions can be made to support the sustainable development of the cold chain in China.

CRedit authorship contribution statement

Yabin Dong: Conceptualization, Methodology, Investigation, Software, Data curation, Visualization, Writing – original draft.
Shelie A. Miller: Funding acquisition, Conceptualization,

Methodology, Supervision, Validation, Writing – review & editing.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2021.126982>.

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