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Greenhouse Gas Emissions from Cold Chains in Agrifood Systems

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Abstract: Cold chains are essential components of agrifood system activities, from storage and food processing to transport, retail, and household consumption. We devise a comprehensive methodology, validated against established data, to estimate both direct (due to refrigerant use) and indirect (from energy use) greenhouse gas emissions from agrifood system cold chains, expanding previous approaches, which had focused on direct emissions only. We found that in 2022, world-total indirect emissions from energy use in cold chains were more than twice the direct component from refrigerants. This resulted in a new estimate of world-total GHG emissions from agrifood system cold chains of 1.32 Gt CO_2eq in 2022, with significant growth over the past two decades (0.52 Gt CO_2eq in 2000). Household consumption and food processing represented the most significant contributors to agrifood system emissions from cold chains, together representing in 2022 three-fourths of the total. These results align well with known global patterns of energy use in the refrigeration sector and highlight the importance of targeting cold chains within agrifood system with GHG emission mitigation actions.

Keywords: greenhouse gas emissions; cold chains; agrifood systems; F-gases; food refrigeration

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1. Introduction

Agrifood systems encompass the farm gate, land use change and pre- and post-agricultural production activities, with significant contributions to anthropogenic greenhouse gas (GHG) emissions, representing approximately one-third of the total [1]. Several recent studies have sought to quantify emissions from post-farm activities with the aim of identifying the highest emitting components, propose energy-efficient technologies, and provide roadmaps and mitigation strategies to support and shape policy decisions for the agrifood sector. According to FAO [1], pre-and post-agricultural production activities encompass a range of operations, including manufacturing of fertilizers and pesticides, food processing, packaging, retailing, transport, household consumption, and waste disposal.

Cold chains are a critical infrastructure of agrifood systems, playing a vital role in preserving perishable food and enabling its distribution from local to global scales. The interconnected processes of precooling, refrigerated transport, storage, and distribution are crucial for maintaining food quality and safety from production to consumption. While it is well understood that a lack of refrigeration capacity is a major driver of food loss globally [2,3], targeted research on the synergies and trade-offs of future cold chains development in agrifood systems with respect to climate and sustainable development goals and targets remains limited [4,5].

As efforts to combat hunger and food insecurity intensify, the demand for refrigeration processes will continue to rise. Therefore, developing sustainable food cold chains with

minimal GHG emissions impact is crucial [6]. Moreover, development of cold chains has important positive spill-over effects across agrifood systems [7].

The direct component of GHG emissions from agrifood system cold chains, i.e., those related to the use of refrigerant F-gases, is available with country detail from FAO [8], showing a world total of 0.52 Gt CO_2eq in the year 2021, with a nearly five-fold increase since the year 2000. Conversely, similarly detailed data on the indirect emissions from agrifood system cold chains, i.e., from energy consumption, do not yet exist. This indirect component may in fact be significant, considering that published global estimates suggest that up to 5% of the worlds' electricity is currently used to operate agrifood system cold chains [9,10].

The quantification of indirect emissions is therefore necessary to better inform and implement effective mitigation actions for sustainable agrifood systems transformation.

In this paper, we estimate for the first time both direct and indirect emissions from agrifood system cold chains, detailing trends at the country, regional and global level. In doing so, we adopt the categorization framework of the International Institute of Refrigeration (IIR) and IPCC [11–13]. (See Table 1).

Table 1. Agrifood system cold chain categories.

This Paper	IIR	IPCC
Food Processing (equipment typically used for chemical processing, cold storage, food processing and cooling)	• Pre-cooling • Cold Storage	• Food processing and cold storage
Food Transport (equipment to preserve and store goods, primarily foodstuffs, during transport by road, rail, air and sea)	• Refrigerated Transport	• Transport refrigeration
Food Retail (equipment used by retail outlets for holding and displaying frozen and fresh food for customers)	• Retail	• Commercial refrigeration
Household (refrigerators and freezers used for food storage, primarily in dwelling units)	• Final Consumer	• Domestic refrigeration

2. Materials and Methods

The total agrifood cold chain emissions for country/region (i) for a selected year (y), in kilotonnes of CO_2 equivalent (kt CO_2eq), was determined using the following formula:

$$E_{i,y} = E_{i,y}^{FP} + E_{i,y}^{FT} + E_{i,y}^{FR} + E_{i,y}^{H}$$

where

- $E_{i,y}$= emissions in country or region i, for year y, in kt CO_2eq;
- $E_{i,y}^{FP}$ = emissions from food processing in country/region i for year y;
- $E_{i,y}^{FT}$ = emissions from food transport in country/region i for year y;
- $E_{i,y}^{FR}$ = emissions from food retail in country/region i for year y;
- $E_{i,y}^{H}$ = emissions from food households in country/region i for year y.

For food processing, food transport, and food retail, the greenhouse gas emissions were calculated by applying the IPCC Tier 1 formula [1,8], as follows:

$$E_{i,y} = A_{i,y} * EF + DE_{i,y}$$

where

- E = emissions in country or region (i), for year (y), in kt of CO_2eq;
- A = activity data for food processing electricity use, in terajoules (TJ), in country/region (i), for year (y);

- EF = emission factor of the national electricity grid;
- DE = direct emissions of F-gas from refrigerant use.

2.1. Food Processing

Food processing is the process of converting raw food materials into consumer good products, which also includes the subsequent use of food cold storage. Refrigeration in food processing is critical to inhibit microbial growth and enzymatic activity. By slowing down these processes, refrigeration helps to extend the shelf life of perishable foods, maintain their quality, and prevent spoilage, particularly for dairy products, meat, fish, fruits, and vegetables. Many food products, particularly perishable ones like meat, seafood, fruits, and vegetables, are routinely frozen to preserve them for extended periods and to support transport, retail and consumption. During food processing, it is crucial, for activities such as cutting, mixing, or packaging to maintain a cold environment to prevent the food from reaching temperatures that could accelerate food spoilage or degradation.

The F-gas emission data used in this calculation, DE, were sourced from FAO [8], together with "food shares" applied to F-gas emissions according to [8]. These activity data inherently pertain to the food sector, excluding F-gas emissions from other sectors such as the pharmaceutical sector. The F-gas emissions at each stage of the agrifood chain are readily available from FAOSTAT in the "Pre and post agricultural production" domain (https://www.fao.org/faostat/en/#data/GPP, accessed on 21 October 2024).

Total F-gases under the IPCC category "Industrial Refrigeration" were adjusted to the characteristics mentioned in Table 2.

Table 2. Representative characteristics of industrial refrigeration [5].

Type of Food Processing	Emissions Charge (kg)	Power Rating (kW)
Large Industrial Units	1000	5000
Small Industrial Units	100	2000

2.2. Food Transport

The transport refrigeration sector aims to maintain optimal temperatures for chilled or frozen food products during transportation. Temperature-controlled warehouses maintain the specific product temperature while the cold storage transport is subjected to fluctuating ambient temperatures and diverse weather scenarios. Due to their operational requirements, transport refrigeration units must be robust and reliable to withstand the rigors of transportation and accommodate a variety of cargo types with specific temperature needs.

Our analysis covers three transportation modes: road, rail, and intermodal systems as described in Figure 1. Food refrigeration on fishing boats and large vessels is excluded from our analysis. Such analysis is too granular for proper identification and should be included in future work.

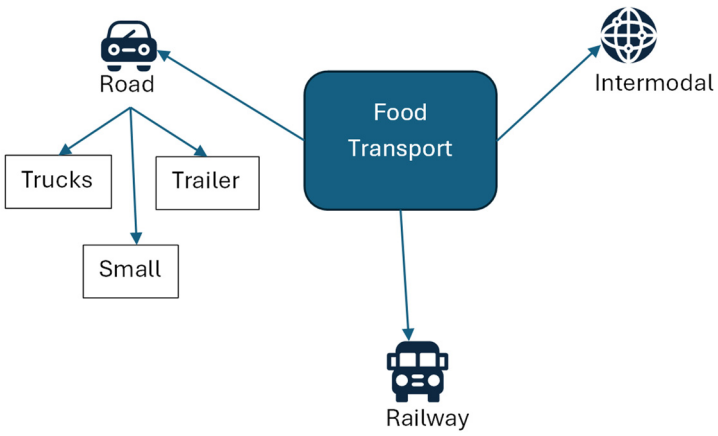


Figure 1. Food transport components quantified in this study.

Road transport includes van, truck, or trailer-mounted systems, predominantly using a mechanical vapor compression cycle. These units are equipped with integrated components such as diesel engines, compressors, condensers, and evaporators, necessary for maintaining the refrigeration cycle during transit. Road systems are widely used for local and long-distance food distribution, with typical refrigerants including HFC-134a for cooling and R-404A for freezing applications.

Railway transport is utilized to transport goods over long distances. Refrigerated railcars employ mechanically driven systems. Historically, these were cooled with CFC-12 but are now predominantly using HFC-134a, in compliance with environmental regulations phasing out CFCs.

Intermodal transport includes refrigerated containers and swap bodies that can transition between sea and land or rail and road. Intermodal units offer flexibility in logistics, allowing cargo to be shipped by rail or road without unloading and reloading the content.

The activity data used in this calculation is sourced from FAO [8]. It is important to note that this activity data inherently pertains to the food sector by default. This default categorization ensures that our emissions calculations accurately reflect the environmental impact of the food cold chain, without including emissions from other sectors such as pharmaceuticals or general industrial refrigeration. Total F-gases under the IPCC category "Transport Refrigeration" were adjusted to the following characteristics (See Table 3):

Table 3. Representative characteristics of food transport [5].

Type of Food Transport	Subsection	Emissions Charge (kg)	Power Rating (kW)
Road Transport	Small	0.45	2
	Trailer	1.69	30
	Trucks	1.125	15
Railway Transport	-	3.38	20
Intermodal Transport	-	1.125	5

2.3. Food Retail

Commercial refrigeration includes three main types of systems: stand-alone units, condensing units, and comprehensive supermarket systems. (See Figure 2):



Figure 2. Food retail components.

Stand-alone units integrate all components into single devices, such as wine and beer coolers, ice cream freezers, beverage vending machines, and various display cases.

These units are commonly placed in small shops, train stations, schools, supermarkets, and corporate buildings. These stand-alone units are widely applied across both industrialized and developing nations, and are the predominant form of commercial refrigeration in many regions of the developing world.

Condensing units are applied in smaller commercial operations and consist of one or two compressors, condensers, and receivers, generally located outside the sales area. These units are paired with display cases or small cold storage rooms. They are common in specialty shops like bakeries and butchers in industrialized nations and larger food retailers in developing countries.

Full supermarket systems are differentiated by their cooling processes: either through direct expansion (direct systems), where refrigerants evaporate within the evaporator, or via an indirect system, where a low-temperature secondary heat transfer fluid (HTF) is centrally cooled and then circulated through a closed loop to the display cabinets and cold stores. Direct systems generally offer higher efficiency and cost benefits.

As for food processing, the activity data used in this calculation were sourced from FAO, whereas the "food shares" applied to F-gas emissions were from Flammini et al. (2023) [5,14]. Total F-gases under the IPCC category "Commercial Refrigeration" were adjusted to the following characteristics (See Table 4):

Table 4. Representative characteristics of food retail [5].

Type of Food Processing	Emissions Charge (kg)	Power Rating (kW)
Stand-alone Units	3	0.7
Condensing Units	50	5
Full Supermarket	1000	20

2.4. Household

Globally, over 80 million domestic refrigerators and freezers are manufactured each year. These appliances are designed for storing food in homes and non-commercial settings such as offices. They vary widely in size, with storage capacities ranging from as little as 20 L to more than 850 L [13].

For household, the greenhouse gas emissions, calculated at IPCC Tier 1, used the general formula:

$$E_{i,y} = A_{i,y} * EF * fs + DE$$

where

- $E_{i,y}$ = household emissions in select country or region i, for select inventory year y, in kt CO_2eq;
- $A_{i,y}$ = activity data for electricity use of refrigerator, in TJ, in country/ region i, for year y;
- EF = emission factor-based grid emissions;
- fs = food share;
- DE = direct F-gas emissions.

Activity data were taken from UNSD energy statistics, Flow 1231: consumption by households [15]. The UNSD data represent official country data from 238 countries and territories. All data were then converted to energy units by applying the IPCC default heating values [16].

In line with Flammini et al. (2023) [8], food shares used in the pre and post agricultural production domain of FAOSTAT were collected from various sources, mainly from the International Energy Agency (IEA) energy efficiency indicators annual reports, complemented by academic journals and reports from government publications. For years when food share data for specific countries and territories were not available, we calculated regional averages, using FAO regions. Direct emissions were taken from those already estimated by FAO [8].

2.5. Limitations

While this study presents a comprehensive methodology for quantifying GHG emissions from the agrifood cold chain, several limitations apply. The methodology relies on IPCC Tier 1, which is based on broad generalizations and assumptions about energy consumption patterns and emission factors in countries. These generalizations may not capture the full variability and complexity of food cold chain operations across different regions and sectors, due, for example, to differences in the quality of the equipment or to different levels of maintenance. At the same time, this approach allows for consistent comparisons across countries, overcoming shortfalls in the availability of more detailed national data.

The accuracy of the activity data used in the calculations is also critical. While efforts were made to obtain localized electricity rates and activity data, there are inherent uncertainties in the data sources, particularly for countries with limited or outdated information. When such data were unavailable, either in terms of activity data or local emission factors, a subregional grid emission factor was applied.

We estimate that, as a result of the above limitations, our results are characterized by an uncertainty of 30–50%. To further refine and improve the understanding of GHG emissions from the food cold chain, future research should focus on refining the methodologies to get a more accurate picture of activity data, food shares and emission factors. This includes obtaining more granular data on energy consumption and refrigeration practices and technologies in different regions and sectors.

Finally, it should be noted that this paper is limited to land-based agricultural production, i.e., it does not address the important role of cold chains in fisheries, mainly for storage and processing of fresh catch in fishing vessels.

3. Results

The new data indicate a steady rise in global agrifood cold chain GHG emissions over the study period, more than doubling over the last two decades, from 0.55 Gt CO_2eq in 2000 to 1.32 Gt CO_2eq in 2022 (Figure 3). This upward trend reflects the growth of the agrifood cold chain system and its associated energy consumption, which also has more than doubled over the same period.

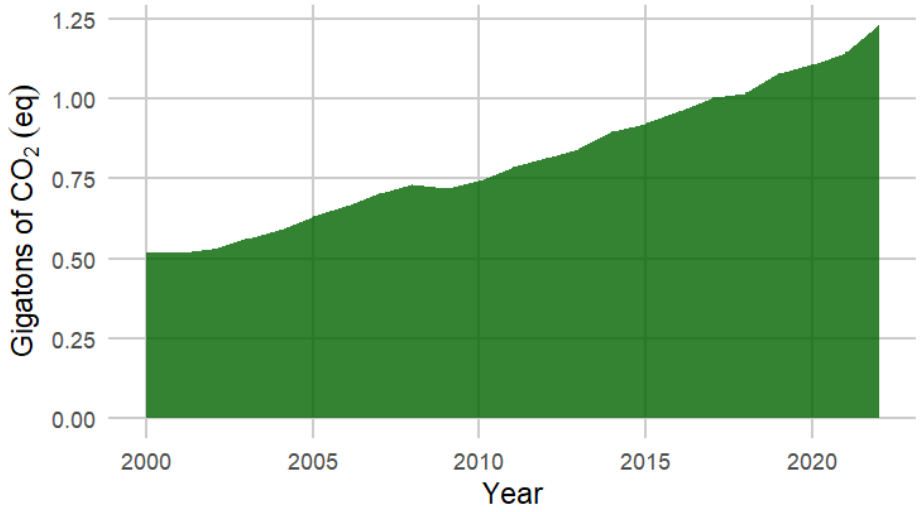


Figure 3. Global food cold chain carbon emissions from 2000 to 2022.

Figure 4 provides a detailed breakdown of cold chain GHG emissions for the year 2022. The household segment was estimated to be the largest contributor, accounting for 0.55 Gt CO_2eq, followed by the food manufacturing industry at 0.42 Gt CO_2eq and food retail, the latter at 0.32 Gt CO_2eq. Conversely, we estimated that food transport contributed only 0.03 Gt CO_2eq. These findings emphasize the critical role of household and food

processing in driving emissions within the cold chain, highlighting the need for targeted interventions in these agrifood systems components in order to enhance energy efficiency and reduce the carbon footprint across agrifood cold chains.

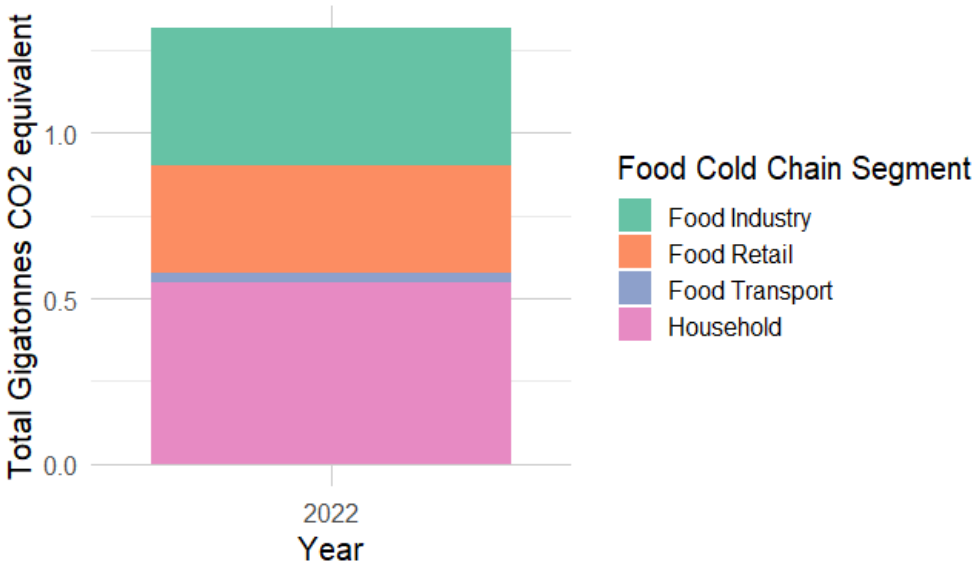


Figure 4. Cold chain emission components for the year 2022.

The agrifood retail segment also saw a significant increase in emissions from 2000 to 2022 (See Figure 5). As shown in Figure 6, emissions rose from 0.04 Gt CO_2eq in 2000 to 0.32 CO_2eq Gt in 2022.

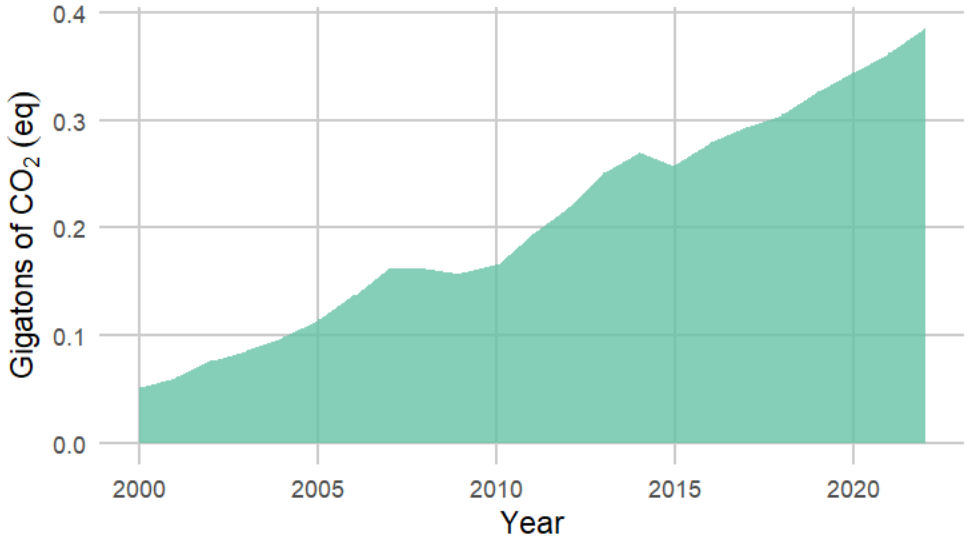


Figure 5. Global food processing industry carbon emissions from refrigeration from 2000 to 2022.

Despite their small contribution to the total, emissions from the agrifood transport segment increased significantly from 2000 to 2022, specifically from 0.005 Gt CO_2eq in 2000 to 0.030 Gt CO_2eq in 2022 (Figure 7).

The household refrigeration segment has maintained relatively high emissions from 2000 to 2022. As shown in Figure 8, emissions fluctuated slightly but generally remained around 0.4 to 0.5 Gt CO_2eq, peaking at 0.55 Gt CO_2eq in 2022.

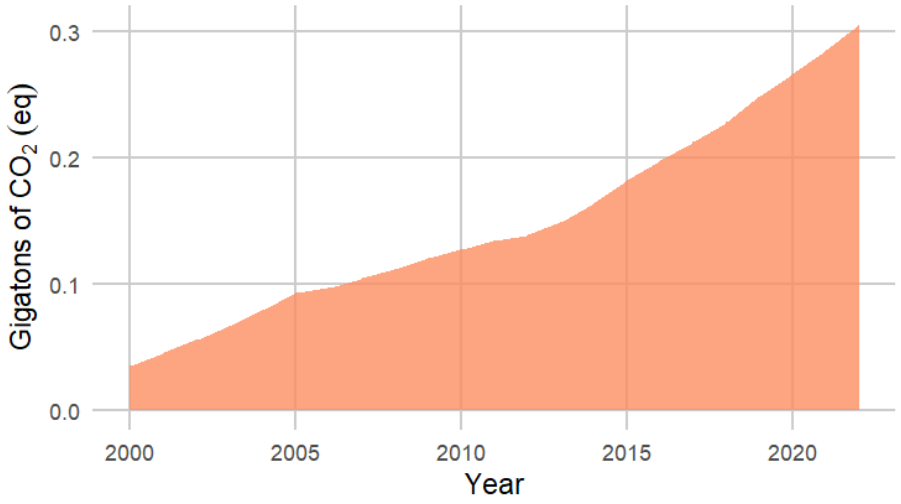


Figure 6. Global food retail carbon emissions from refrigeration from 2000 to 2022.

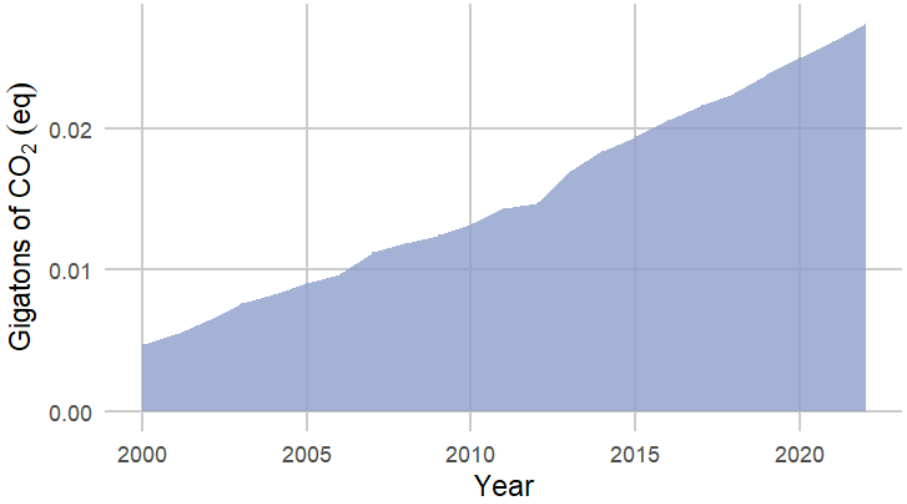


Figure 7. Global food transport carbon emissions from refrigeration from 2000 to 2022.

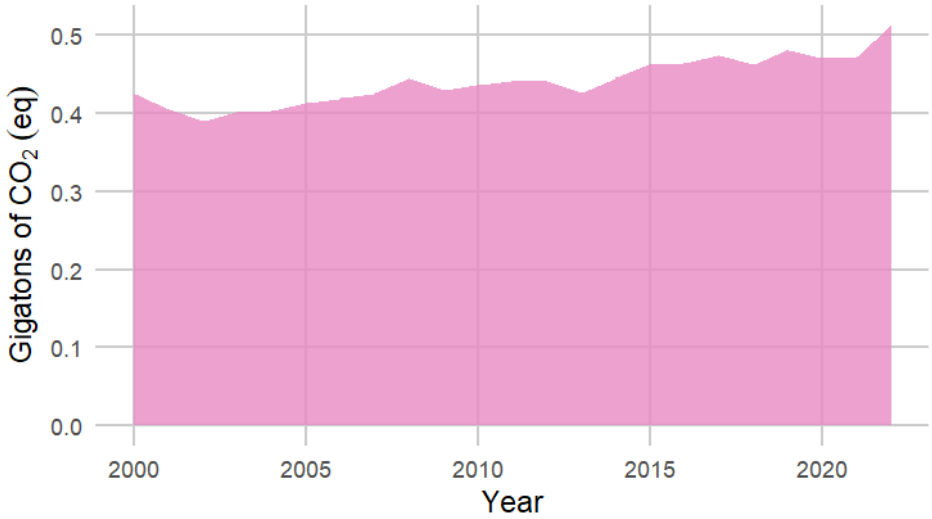


Figure 8. Global food household carbon emissions from refrigeration from 2000 to 2022.

Validation

For each sector, the calculated indirect emissions were a linear function of the electricity consumption of the refrigeration equipment. Therefore, the validation of the proportionality of emissions was performed through energy consumption studies. The International Institute of Refrigeration (IIR) estimates that the distribution of the global refrigeration sector's electricity consumption is 15.4% for the residential sector, 39.4% for the tertiary sector, and 45% for the industrial sector. The following mapping table allows for a map-to-map comparison [17]. (See Table 5).

Table 5. Map-to-map comparison between IIR and this paper.

IIR	This Study
Residential Sector	Household
Tertiary Sector	Food Retail
	Food Transport
Industrial Sector	Food Industry

While our study shows a good alignment with the IIR data in terms of category definitions and distribution, there are significant deviations in the percentages for certain categories. The industrial sector in the IIR data (45%) is close to our food industry category (41.4%). The residential sector (IIR: 14.5%) is comparable to our household category (31.5%), though higher in our study. The tertiary sector (IIR: 39.4%) maps to both food retail (24.4%) and food transport (2.2%), which combined still show a noticeable deviation from the IIR data. In summary, our approach results in a higher estimate of GHG emissions from refrigeration in the household sector and lower emissions from refrigeration in retail and transport (combined) as compared to IIR estimates. At the same time, the IIR data confirm the household sector as the dominant contributor to the overall cold chain impacts. (See Figure 9).

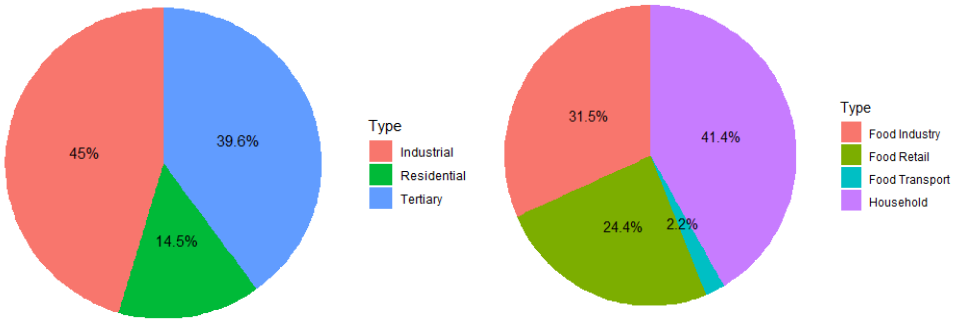


Figure 9. Distribution of the global refrigeration sector's electricity consumption (%) [17]; distribution of the global emissions from energy use in cold chains.

These deviations suggest that while the overall results align, there are substantial differences in the percentage allocations, which could also be associated with discrepancies in either the energy consumption or the emission factors used. Estimates of uncertainty and further investigation of results will be required to better qualify and understand the causes of these discrepancies.

A study published in the Annual Review of Environment and Resources calculated the greenhouse gas (GHG) emissions of the cooling and refrigeration industry [18]. (See Figure 10). Their category mapping aligns well with our category definitions. (See Table 6).

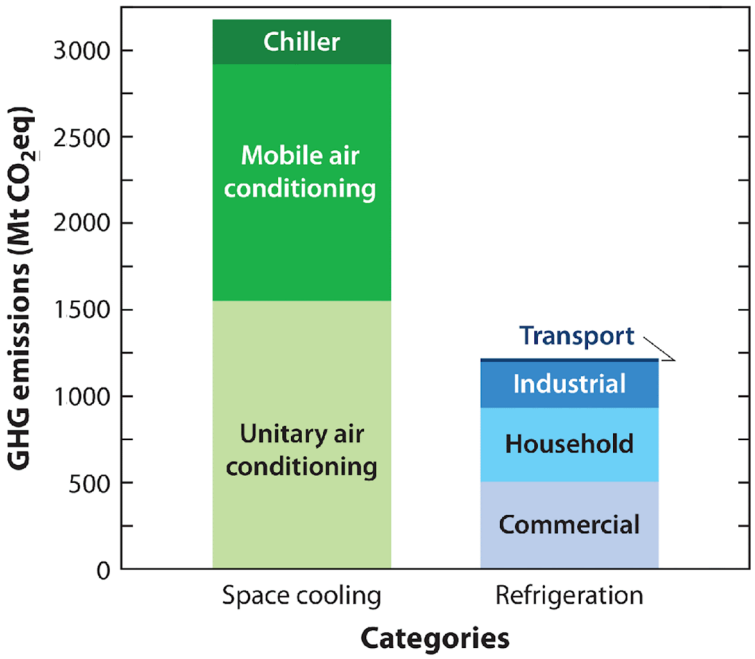


Figure 10. GHG emissions from refrigeration applications in 2020 [18].

Table 6. Map-to-map comparison between Dong et al., 2021 [18] and this study.

Dong et al., 2021	This Study
Transport	Food Transport
Industrial	Food Industry
Household	Household
Commercial	Food Retail

This study estimated total emissions from the refrigeration sector across the four sectors as 1.25 Gt of CO_2eq. This is in good agreement with the main findings of the current study, estimating emissions from the food cold chain as 1.18 Gt for 2020, closely aligned with the results of our methodology. (See Figure 11).

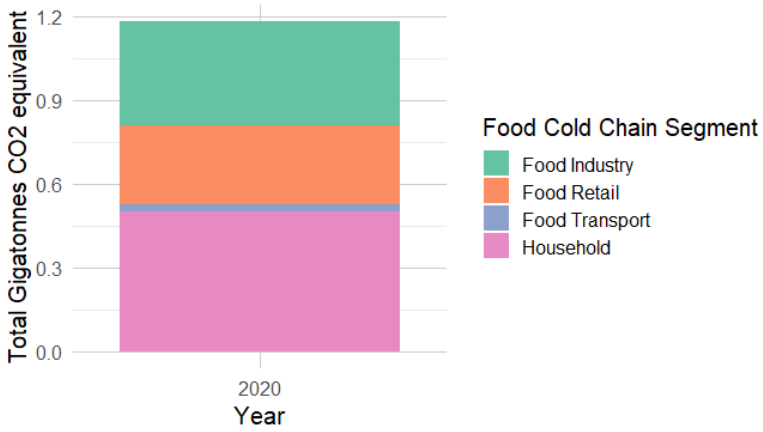


Figure 11. Cold chain emissions breakdown for the year 2020, according to this study.

4. Discussion

The results of this study highlight the significant contribution of the agrifood cold chain to global GHG emissions. With a steady increase from 0.55 Gt CO_2eq in 2000 to 1.32 Gt CO_2eq in 2022, GHG emissions from food refrigeration energy use are on the rise. Based on

previously published data, the global agrifood systems F-gas direct emissions were 0.10 Gt CO_2eq in 2001 and 0.52 Gt CO_2eq in 2021. Therefore, our results show that indirect energy emissions were several fold the direct emissions component, and specifically twice as large in 2022.

The household refrigeration segment was estimated to be the largest contributor to GHG emissions within the food cold chain, accounting for 0.55 Gt in 2022. This was attributed to the widespread use of domestic refrigerators and freezers used for food preservation in most households globally. The relatively high and stable emissions from this segment over the study period highlight the need for improved energy efficiency in household refrigeration appliances as a critical component of cold chain based mitigation strategies.

The agrifood manufacturing industry and agrifood retail segments also contributed substantially to cold chain emissions. The food industry's emissions increased from 0.057 Gt in 2000 to 0.42 Gt in 2022, while food retail emissions rose from 0.037 Gt to 0.32 Gt over the same period. The growth in these segments points to the potential impact of targeted interventions to enhance energy efficiency and reduce emissions.

Our findings align well with the distribution of global refrigeration sector emissions reported by the IIR and other studies, such as Dong et al. (2021) [18]. The proportional distribution of emissions across the household, food retail, food transport, and food industry segments in our study is consistent with the electricity consumption patterns of the refrigeration sector reported by the IIR. The close alignment with Dong et al.'s estimates further validates our methodology and underscores the reliability of our results.

Future research should focus on refining the methodologies developed herein as a first approach for estimating GHG emissions from the agrifood cold chain. This includes improving the accuracy of the activity data and emission factors and exploring the technical characteristics and adoption rate of different refrigeration technologies and practices. Secondly, future work should also include collaborations with industry stakeholders, policymakers, and researchers to identify and implement effective GHG mitigation strategies for the agrifood cold chain. Promoting best practices, investing in research and development for advanced refrigeration technologies, and creating supportive regulatory frameworks will need to be essential components of effective mitigation strategies in the agrifood cold chain sector.

5. Conclusions

A new methodology was developed and applied at the country level, with global coverage and over the period 2000–2022, to estimate total direct and indirect GHG emissions from agrifood system cold chains, by the agrifood systems component. Our findings highlight the important contribution of the indirect component of agrifood cold chain emissions, leading to estimates that are as much as three times the levels previously estimated based on direct emissions (F-gases) alone. We found that world-total GHG emissions in agrifood system cold chains were 1.32 Gt CO_2eq in 2022—nearly 10% of the agrifood systems total. Our study further conducted an analysis of cold chain emissions by the agrifood systems component. The results showed the critical contribution of household consumption and food processing, representing about three-quarters of the agrifood systems cold chain total.

Based on the limitations identified in this paper, future improvements include the use of regional or country specific coefficients to better describe the different contexts and refrigeration technologies currently adopted around the world and their trends. This will require significant resources to fund additional efforts through literature searches and country work. Another important area of improvement requires inclusion of the fisheries sector to better quantify the impact of cold chain storage and processing on fishing vessels during navigation.

Within the uncertainties discussed, our study nonetheless represents the state-of-the art of the assessment of the current status and trends in agrifood system cold chain emissions from both energy and refrigerant use. To this end, it represents an important

reference for global statistics, while enabling the identification of critical, targeted mitigation actions in agrifood systems. It facilitates a first-order analysis of country, regional, and global priorities needed for agrifood systems transformation, highlighting through long time-series data and country detail where future opportunities lie for improvements in the energy efficiency and refrigeration practices across the globe.

Author Contributions: A.F. conceptualized the paper and the methodology; H.A. and A.F. prepared the original draft; H.A. supported the data analysis and visualization; R.P., Y.A., H.A. and A.F. edited the paper; and F.N.T., R.P., K.K. and Y.A. reviewed the final draft of the paper. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data used in this study are openly available in FAOSTAT (https://www.fao.org/faostat/en/#data/GPP) and EDGAR (https://edgar.jrc.ec.europa.eu/) and will be made publicly available in FAOSTAT.

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Conflicts of Interest: Author Richard Pattison was employed by the company CrossnoKaye. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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