Food and Agriculture
Organization of the
United Nations

FAO Statistics Working Paper Series

Issue 23/35

# METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM FOOD SYSTEMS
## PART VI: FLUORINATED GAS EMISSIONS

FAO Statistics Working Paper Series / 23-35

# METHODS FOR ESTIMATING GREENHOUSE GAS EMISSIONS FROM FOOD SYSTEMS

## PART VI: FLUORINATED GAS EMISSIONS

Alessandro Flammini, Kevin Karl, Dakshesh Thacker and Francesco N. Tubiello

Food and Agriculture Organization of the United Nations
Rome, 2023

Required citation:
Flammini, A., Karl, K., Thacker, D., Tubiello, N.F. 2023. *Methods for estimating greenhouse gas emissions from food systems. Part VI: fluorinated gas emissions*. FAO Statistics Working Paper Series, No. 35. Rome. https://doi.org/10.4060/cc5403en

The designations employed and the presentation of material in this information product do not imply the expression of any opinion whatsoever on the part of the Food and Agriculture Organization of the United Nations (FAO) concerning the legal or development status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. The mention of specific companies or products of manufacturers, whether or not these have been patented, does not imply that these have been endorsed or recommended by FAO in preference to others of a similar nature that are not mentioned.

The views expressed in this information product are those of the author(s) and do not necessarily reflect the views or policies of FAO.

ISBN 978-92-5-137821-2

© FAO, 2023

Some rights reserved. This work is made available under the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 IGO licence (CC BY-NC-SA 3.0 IGO; https://creativecommons.org/licenses/by-nc-sa/3.0/igo/legalcode).

Under the terms of this licence, this work may be copied, redistributed and adapted for non-commercial purposes, provided that the work is appropriately cited. In any use of this work, there should be no suggestion that FAO endorses any specific organization, products or services. The use of the FAO logo is not permitted. If the work is adapted, then it must be licensed under the same or equivalent Creative Commons licence. If a translation of this work is created, it must include the following disclaimer along with the required citation: “This translation was not created by the Food and Agriculture Organization of the United Nations (FAO). FAO is not responsible for the content or accuracy of this translation. The original [Language] edition shall be the authoritative edition.”

Disputes arising under the licence that cannot be settled amicably will be resolved by mediation and arbitration as described in Article 8 of the licence except as otherwise provided herein. The applicable mediation rules will be the mediation rules of the World Intellectual Property Organization http://www.wipo.int/amc/en/mediation/rules and any arbitration will be conducted in accordance with the Arbitration Rules of the United Nations Commission on International Trade Law (UNCITRAL).

**Third-party materials.** Users wishing to reuse material from this work that is attributed to a third party, such as tables, figures or images, are responsible for determining whether permission is needed for that reuse and for obtaining permission from the copyright holder. The risk of claims resulting from infringement of any third-party-owned component in the work rests solely with the user.

**Sales, rights and licensing**. FAO information products are available on the FAO website (www.fao.org/publications) and can be purchased through publications-sales@fao.org. Requests for commercial use should be submitted via: www.fao.org/contact-us/licence-request. Queries regarding rights and licensing should be submitted to: copyright@fao.org

# Abstract

This paper follows several other papers in the ESS Working Paper series that detail new methodologies for estimating key components of agrifood systems emissions. It describes methods for estimating greenhouse gas (GHG) emissions from the agrifood system, and in particular fluorinated gases (F-gases) from refrigeration systems in the agrifood system cold chain, from food processing to food transport, retailing and household consumption processes. Based on the proposed methodology, we build a new database of GHG emissions from F-gases used in the agrifood system, by country and with global coverage, for the period 1990–2021. We measure the emissions of four F-gases: difluoromethane (R-32), pentafluoroethane (R-125), 1,1,1,2-tetrafluoroethane (R-134a) and 1,1,1-trifluoroethane (R-143a), which represent the bulk of F-gas emissions of the agrifood chain.

This paper focuses on the methodology itself, which involves calculating GHG emissions using activity data, food shares and emission factors. The methodology also addresses the imputation of missing data for commercial, transport and domestic refrigeration, enabling a more accurate representation of F-gas emissions in the agrifood system. Through this methodology, we find that that global agrifood systems F-gas emissions have grown from 0.10 billion tonnes of carbon dioxide equivalent (Gt $CO_2$eq) in 2001 to 0.52 Gt $CO_2$eq in 2021, an increase of over 500 percent. The largest share is attributed to food retail, which accounted for 80 percent of the F-gas emissions expressed in $CO_2$eq in 2021. Among countries, China, the United States of America and India had the highest agrifood system F-gas emissions in 2021, emitting roughly 115 million tonnes $CO_2$eq (Mt $CO_2$eq), 60 Mt $CO_2$eq and 54 Mt $CO_2$eq, respectively.

While the paper does provide insights into the growth of agrifood system F-gas emissions and their distribution among countries and sectors, the primary contribution lies in the development of the methodology, which facilitates a more comprehensive understanding of agrifood system emissions and supports progress towards achieving the Sustainable Development Goals (SDGs), particularly SDG 12.

# Contents

# Acknowledgements

This paper has been drafted by Alessandro Flammini, Kevin Karl, Dakshesh Thacker and Francesco Tubiello, with methodological assistance from Carolyne Barker.

Many principles of this methodology were built on previous work by the Food and Agriculture Organization of the United Nations (FAO) on the use of energy in agrifood systems, led by Olivier Dubois. We are thankful to Cynthia Rosenzweig, Philippe Benoit, David Sandalow, Matthew Hayek and the Food Climate Partnership for their useful inputs and comments, which helped to improve the quality of this work. We are also thankful to Leonardo Sousa at the United Nations Statistics Division (UNSD) for support with data provision, the Emissions Database for Global Atmospheric Research (EDGAR) team, whose Global Greenhouse Gas Emissions v7.0 dataset forms the basis of this analysis, and to Yunrui Zhou at the Montreal Protocol Unit of the United Nations Industrial Development Organization (UNIDO), Erik Mencos Contreras at the Center for Climate Systems Research at Columbia University, Alan Foster at the Heating and Cooling Group of the London South Bank University for peer-reviewing the paper.

# 1 Introduction

Agrifood systems are significant contributors to global greenhouse gas (GHG) emissions, with existing literature focusing on farm activities, land-use change, and pre-farm-gate activities. However, a critical gap remains in the understanding of post-farm-gate emissions, particularly those associated with pre- and post-production processes such as refrigeration throughout the food chain. While previous studies have provided initial insights into GHG emissions along the entire food chain (Sims *et al.*, 2011), recent advancements by Crippa *et al.* (2021a) and Tubiello *et al.* (2021) have significantly improved the methodological basis for quantifying agrifood systems emissions.

This work improves previous efforts by providing a more comprehensive and granular estimation of fluorinated gas (F-gas) emissions across four agrifood system categories: (1) industrial refrigeration; (2) transport refrigeration; (3) commercial refrigeration; and (4) domestic refrigeration. We specifically measure the emission of four F-gases at each of these four steps: difluoromethane (R-32), pentafluoroethane (R-125), 1,1,1,2-tetrafluoroethane (R-134a), and 1,1,1-trifluoroethane (R-143a). This novel methodology offers a more accurate and detailed understanding of F-gas emissions from the cold chain, which has not been achieved in previous studies.

The overarching goal of this work is to disseminate country-level statistics on GHG emissions from agrifood systems through FAOSTAT, with annual updates and global coverage. Our study helps better characterize agrifood systems and highlights their role in achieving the Sustainable Development Goals (SDGs). Furthermore, this research contributes to bridging the gap between statistics on agrifood systems reported to FAO and those reported under the United Nations Framework Convention on Climate Change (UNFCCC).

In addition to our focus on F-gas emissions, we acknowledge complementary work that estimates GHG emissions from other agrifood system processes (Tubiello *et al.*, 2021), such as food transport (Karl and Tubiello, 2021a), waste disposal (Karl and Tubiello, 2021b), on-farm energy use (Flammini *et al.*, 2022), and emissions from food consumption in households (Flammini *et al.*, 2023a; Flammini *et al.*, 2023b).

This paper begins with an introduction of the cold chain process, and then moves to the methodology of quantifying F-gas emissions and the rationale to calculate refrigeration “food shares” for the relevant food chain components. Finally, the paper discusses limitations and uncertainties associated with this methodology and a proposed way forward.

# 2 The cold chain in food systems

## 2.1 Context

In 2021, agrifood system emissions amounted to 16.1 Gt $CO_2$eq per year globally, representing 34 percent of total anthropogenic GHG emissions (FAO, 2022). The largest contribution came from farm-gate activities (46 percent), followed by pre- and post-production activities (35 percent), and finally land-use change activities (19 percent) (FAO, 2022). Pre- and post-production activities include, but are not limited to, fertilizers manufacturing, electricity and heat production (taking place outside the farm) for on-farm use, food processing, food packaging, food retail, food transport, household food consumption and food systems waste disposal (Tubiello *et al.*, 2021a).

Food cold chains play a vital role in maintaining food security by reducing post-harvest losses and extending the shelf life of perishable products (Göransson *et al*., 2018). These systems encompass a series of interconnected activities – including precooling, refrigerated transport, storage and distribution – which ensure the preservation of food quality and safety from production to consumption (IIR, 2018). Well-developed cold chain infrastructure can significantly minimize food loss and waste, enhance access to diverse and nutritious diets, and contribute to the stability of local and global agrifood systems (FAO, 2021).

However, conventional cold chain systems are often energy-intensive and rely heavily on fossil fuels, contributing to greenhouse gas emissions and exacerbating climate change (IRENA and FAO, 2021). In addition to contributing to climate change via the combustion of fossil fuels for energy (indirect emissions) to run cold chain activities (e.g. refrigerated aisles in grocery stores), cold chains also emit potent greenhouse gases through the leakage of F-gases from refrigerants (direct emissions) (Heredia-Aricapa *et al.*, 2020). This study focuses only on the “fugitive emissions” of food cold chains, which are a minor part of total GHG emissions from food cold chains. In addition, it focuses only on cold chains, excluding air conditioning, such as for cooling trucks’ cabins or for pre-cooling of food (e.g. in certain cold rooms).

Cold generation systems initially utilized various natural refrigerants, such as ethyl-ether in 1834, carbon dioxide, ammonia and hydrocarbons, some of which were toxic and flammable, leading to the evolution of refrigerants with a key focus on safety (Duarte *et al.*, 2017). Chlorofluorocarbons (CFCs) began to proliferate in the 1930s, while hydrochlorofluorocarbons (HCFCs) followed around 1950, and hydrofluorocarbons (HFCs) in the 1990s, that latter of which emerged as a result of the Montreal Protocol's restrictions on ozone-depleting CFCs and HCFCs (Domanski *et al.*, 2018). While HFCs offer comparably low acquisition costs, no flame propagation, chemical stability and good thermodynamic properties, they are potent greenhouse gases (Velders, 2019). FAO estimated that 0.44 Gt $CO_2$eq of F-gas emissions from food retail in 2020 stemmed from the leakage of HFC-based F-gases from commercial refrigeration systems (FAO, 2022).

The Intergovernmental Panel on Climate Change (IPCC) reporting structure for refrigeration includes four key steps: industrial refrigeration, transport refrigeration, commercial refrigeration and domestic refrigeration (IPCC, 2006). The International Institute of Refrigeration (IIR) also has a framework for categorizing agrifood system cold chains, placing cooling activities into pre-cooling, refrigerated transport, cold storage, retail sales and consumer usage stages (IIR, 2019). The EDGAR 7.0 database uses the IPCC

1996 structure for refrigeration and classifies data into the four IPCC buckets listed above (EDGAR 7.0, 2022).

This effort is based on IPCC categorizations, which are mapped to FAOSTAT pre- and post-production emissions categories, as described in Table 1 below. The main refrigerants utilized in each stage are taken from the IIR report on the carbon footprint of the food cold chain (IIR, 2019).

**Table 1.** Steps in the agrifood system cold chain, according to the IPCC, IIR and FAOSTAT

| IPCC framework | IIR framework | FAOSTAT framework | Main F-gas refrigerants used (IIR) | Hydrofluorocarbons considered from EDGAR 7.0 |
|---|---|---|---|---|
| Industrial refrigeration | Cold storage | Food processing | R-404A | HFC-125, HFC-134a, HFC-143a, HFC-32 |
| Transport refrigeration | Refrigerated transport | Food transport | R-404A and R-452A | |
| Commercial refrigeration[1] | Retail sales | Food retail | R-404A | |
| Domestic refrigeration | Consumer usage | Food consumption | R-134A | |

Source: Authors' own elaboration.

R-134A, R-404A and R-452A are HFC-based refrigerants, with the latter two being a mixture of multiple HFCs. R-404A comprises HFC-125, HFC-134a and HFC-143a, each respectively constituting 44 percent, 4 percent and 52 percent of the composition. Similarly, R-452A comprises HFC-125, HFC-32 and HFO-1234yf, which each respectively constitute 59 percent, 11 percent and 30 percent of the composition (Heredia-Aricapa *et al.*, 2020). This analysis utilizes F-gas emissions data relevant to the agrifood system cold chain, which are almost entirely emitted during the life cycle of the refrigeration systems' equipment through leakage. For example, R-143a, the most common hydrofluorocarbon used in refrigeration systems, leaks into the atmosphere because of faulty equipment or improper disposal (C2ES, 2019). Hence, we classify agrifood system F-gas emissions under "banked emissions" according to the IPCC (IPCC, 2019).

---

[1] This includes supermarkets and other sales outlets.

# 3 Methodology

According to the IPCC Guidelines (IPCC, 2006), GHG emissions are calculated at Tier 1 using the general formula:

$E = A * EF$

where

$E$ = emissions in $CO_2$ equivalent (kg $CO_2$eq),

$A$ = activity data, the amount of F-gas released in the atmosphere (kg),

$EF$ = emission factor, according to the global warming potential (GWP) of each of the F-gases.

This methodology builds on previous on publications in this series, such as Karl and Tubiello (2021a) for food transport, Karl and Tubiello (2021b) for agrifood systems waste disposal, on-farm energy use, Flammini *et al.* (2022) for on-farm energy use, and Flammini *et al.* (2023a, 2023b) for food consumption in households. These papers refer to the concept of food share, by which we mean the estimate of the portion of total emissions that are attributable to agrifood system activities. For F-gas emissions estimations, the calculation then becomes:

$E_f = A * EF * FS$

where

$E_f$ = agrifood system-related emissions in $CO_2$ equivalent ($CO_2$eq),

$A$ = activity data, the amount of F-gas released in the atmosphere (kg),

$EF$ = emission factor, according to the global warming potential of each of the F-gases,

$FS$ = food share, the share of F-gas leakage which is attributable to the agrifood system.

## 3.1 Activity data

Activity data were extracted from the EDGAR v7.0 database, which covers multiple F-gases, including those outside the agrifood system, for the period 1990–2021. F-gases for relevant agrifood system components were identified and an appropriate refrigerant share was utilized for each of the constituent F-gases. For example, HFC-125 is used in fire extinguishers, mobile and stationary air conditioners as well as production of halocarbons and in the semiconductor industry. As a result, only relevant items of usage to agrifood systems cold chains, listed in Table 1, were considered to estimate emissions in agrifood systems.

Activity data were available only for some countries and agrifood system components. For example, in 2021, domestic refrigeration emissions data are only available for 38 countries, industrial refrigeration data for 25 countries and refrigerated transport data for 42 countries. Data on HFC leakage from commercial refrigeration are much better represented, with data available for 125 countries.

### 3.1.1 Imputation of missing country activity data

Missing data on industrial refrigeration are not imputed, as it is not assumed that all countries have extensive food processing refrigeration networks. However, missing data for commercial, transport and domestic refrigeration are imputed, as it is assumed that most countries have some form of food refrigeration in commercial, domestic and transportation activities.

Missing data are imputed according to the following steps:

1) In countries where data are available on HFC emissions (HFC-32, HFC-125, HFC-134a, or HFC-143a) on a cold chain step (industrial, transport, commercial or domestic refrigeration), the per capita emissions for that HFC in that step are calculated. Population data comes from the World Bank Open Data database.

2) Subregional per capita emissions means are then computed according to FAOSTAT subregional geographic categories, using the M49 classification (e.g. Eastern Africa, Middle Africa, Northern Africa). These means are year-specific, cold chain step-specific, and HFC- specific.

3) Where subregional per capita emissions values are available, missing country data for commercial, domestic or transport refrigeration emissions are imputed by multiplying the country's population by subregional per-capita emissions for that specific cold chain step and HFC combination in a given year.

For countries where no subregional values are present, missing data are imputed in the following way:

1) First, the relationships between subregional means for different cold chain steps is determined, such that there is a ratio between the per capita emissions of commercial refrigeration to the total per capita emissions from food chains in a given country each year. The ratio for food-related domestic and transport subregional refrigeration emissions means to total food-related cold chain emission is also calculated.

2) The same is performed for the HFCs: a ratio of each HFC (e.g. HFC-32) to total food-HFC emissions in a country each year is computed.

3) Next, missing data are imputed, according to subregional values as follows:

    a. If a value is missing for both an HFC and cold chain step, the total F-gas emissions value, as reported by the PRIMAP dataset (PRIMAP, 2021) is multiplied by the ratio of that step to the total, and then further multiplied by the ratio of that HFC to the total.

    b. The results of this final imputation method are that the subregional ratios of F-gas emissions across the cold chain steps and specific-HFCs is captured and transferred to countries that have total sectoral data in PRIMAP to increase granularity and coverage relative to the original EDGAR dataset.

### 3.1.2 Imputation formula

The imputation methodology can be described mathematically as follows:

1. $PC_{C,S,H,Y}$ = ($HFC\_Emissions_{C,S,H,Y}$ / $P_{C,Y}$ ) for available data

2. $SR_{S,H,Y}$ = mean($PC_{S,H,Y}$) for each H, S, and Y in each subregion

3. $E\_missing_{C,S,H,Y} = SRE_{S,H,Y} * P_{C,Y}$ for missing data where subregional S, H and Y data are available
4. If no subregional data are available:
    (i) Calculate ratios:
        a) $Ratio\_chain\_step_{C,S,Y} = (E_{C,S,Y} / Total\_F\text{-}gas\_Emissions_{C,Y})$
        b) $Ratio\_HFC = (E_{C,H,Y} / Total\_F\text{-}gas\_Emissions_{C,Y})$
    (ii) Impute missing data:
        a) $E\_missing_{C,S,H,Y} = Total\_F\text{-}gas\_Emissions_{C,Y} * Ratio\_chain\_step_{C,S,Y} * Ratio\_HFC_{C,H,Y}$

Where:

- C: Country
- S: Cold chain step (transport, industrial, commercial, or domestic refrigeration)
- H: HFC type (HFC-32, HFC-125, HFC-134a, or HFC-143a)
- Y: Year
- P: Population
- PC: Country per capita emissions
- SR: Subregional per capita emissions
- E: Emissions

## 3.2 Food shares

Refrigeration has applications outside agrifood systems, the most prominent of which is preserving and storing vaccines and other pharmaceutical drugs (Pambudi *et al.*, 2022). Only F-gas emissions used for agrifood systems from the EDGAR v7.0 dataset were considered. Others related to air conditioning, solvents and aerosols were excluded. In addition, due to additional applications of refrigeration, especially for commercial and transportation, we estimated “food shares” to reflect the shares of global use of a certain F-gas applied to each of the four steps of the cold chain. For each of the four steps, the food share of F-gases was estimated based on the available literature.

Refrigerators in the households are almost entirely used for cooling food and beverages (IPCC, 2005). Hence, the food share of F-gas to agrifood systems in the households (food consumption) was set to unity.

Refrigerators used for commercial purposes are almost entirely used for cooling food and beverages, mapped to food retail. However, a part of commercial usage can also be attributed to over-the-counter pharmacies that also use refrigerators to store and preserve medicines. However, we have a lack of data of the exact number of refrigerators used for pharmacy and drug stores compared to refrigerators used for food retail. We assumed a 90 percent food share for commercial refrigeration.

Transport refrigeration is also required for vaccination and pharmaceutical drugs (IIR-UNEP, 2018). Given the paucity of data of the exact percentage share of refrigerants used for vaccinations, a 90 percent food share was assumed based on expert judgement.

The IPCC definition of industrial refrigeration (food processing) includes a wide range of cooling and freezing applications in the chemical, oil and gas industries as well as in industrial ice-making, air liquefaction and other related industry applications. Of these listed processes, ice-making can still be considered to have agrifood systems applications. However, the exact percentage of food-related uses is not clear, and a 90 percent food share was assumed based on expert judgement.

## 3.3 Emission factors

Emission factors are based on the IPCC Fifth Assessment Report (IPCC, 2014) and are shown in Table 2.

**Table 2.** Emission factors by F-gas

| Fluorinated gas | Global warming potential as per AR5 |
|---|---|
| HFC-32 | 677 |
| HFC-125 | 3 170 |
| HFC-134a | 1 300 |
| HFC-143a | 4 800 |

Source: IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

# 4 Limitations and areas for advancement

## 4.1 Limitations of this analysis

The scope of this work does not include energy consumption of food cold chains and is therefore not representative of total GHG emissions associated with food refrigeration. The emissions associated with energy use in food retail environments, food transport, food processing and household food consumption are covered elsewhere in FAOSTAT (Tubiello *et al.*, 2021a), although the share attributable to refrigeration is not disaggregated. Emissions from food refrigeration energy use are expected to be non-negligible (see for example Foster *et al.* 2023, for the United Kingdom of Great Britain and Northern Ireland). In addition, the estimate had to rely on limited available information on the actual "food shares" of different components of the cold chain, especially in the food processing and transport components.

## 4.2 Uncertainty

Uncertainty was introduced by the imputation process and the possible ambiguity in food shares, which are difficult to determine specifically for each F-gas for each country with the current limited information to make specific estimates. Additional uncertainty is associated with the IPCC emission factors (quantified) and the activity data imputation process (not quantified). Uncertainty in the estimation process comes from various sources, including data availability, quality and imputation methods. First, data availability can be a major source of uncertainty, as missing or incomplete data can limit the accuracy and representativeness of the results. When data is unavailable for specific countries, HFC types or cold chain steps, estimations must rely on subregional or regional averages, which may not accurately reflect the local conditions and trends in a given country. Moreover, the quality of available data can be compromised due to differences in data collection methodologies, definitions or reporting standards across countries and sectors, which may introduce inconsistencies and biases in the estimations.

The imputation methods employed to fill in missing data also contribute to the uncertainty in the estimation process. When using subregional or regional means to impute missing data, the assumption is that these averages are representative of the country in question, which might not always be the case. Different countries within a region or subregion may exhibit unique patterns or characteristics that cannot be fully captured by an average value. Furthermore, the relationships between cold chain steps and HFC emissions might not be constant across countries and time periods, leading to potential inaccuracies in the imputed data. As a result, the uncertainty in the imputation methods could propagate throughout the estimation process, affecting the reliability of the overall results and their applicability in informing decision-making and policy development.

## 4.3 Areas for advancement

One potential approach to improving the estimation work is to incorporate machine learning techniques for imputing missing data. These techniques can leverage patterns and correlations in the available data to predict missing values with a higher accuracy than traditional interpolation methods. For example, advanced algorithms such as k-nearest neighbours, decision trees, or deep learning models could be employed to predict missing HFC emissions and cold chain step data based on various factors including the geographic location, socio-economic indicators and historical trends. Implementing these algorithms would require a comprehensive analysis of existing data to identify the most relevant features and model configurations that best capture the relationships between variables, thereby enhancing the accuracy of imputed data.

Another possible avenue for improvement lies in expanding the range and quality of data sources used in the estimation process. Integrating additional datasets – such as industry-specific sources, private sector companies or remote-sensing activities – and exploring alternative sources of information can make the estimation work more robust and reliable. This may include incorporating remote sensing data to monitor refrigeration activities, exploring industry-specific databases for more granular information on HFC usage or engaging with stakeholders, including government institutions and the private sector, to collect and share data on a more comprehensive and frequent basis.

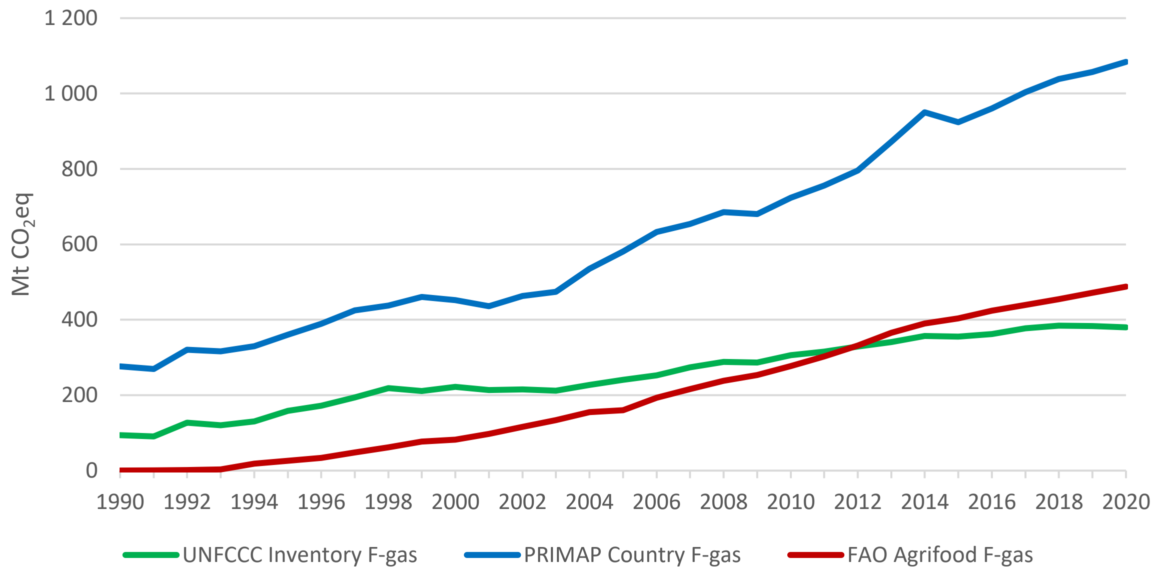
Additionally, efforts should be made to standardize and harmonize data collection methodologies across countries and sectors to ensure that estimates are consistent and comparable. By enriching the data sources and improving data quality, the estimation work can become more accurate and better equipped to inform decision-making in areas like policy formulation and emissions reduction initiatives.

# 5 Validation and results

## 5.1 Global validation

To our knowledge, no other dataset estimates F-gas emissions from agrifood system cold chains disaggregated by country and cold chain step. However, two datasets provide estimates for country total F-gas emissions: the PRIMAP dataset and the UNFCCC inventory. The PRIMAP dataset utilizes third-party inventories in addition to data provided by countries, while the UNFCCC dataset only has data provided by countries to the UNFCCC (43 Annex I countries). Given that our global estimates are computed by aggregating agrifood system emissions across four HFCs and four cold chain steps per country per year, we can only utilize the independent global data (which also include non-agrifood emissions) to ascertain whether the agrifood estimated trends and magnitude are indeed reasonable when aggregated at the global level. We find that the results of this process fit firmly within established inventories for greenhouse gas emissions from fluorinated gases (Figure 1).

**Figure 1.** F-gas emissions estimates by source in Annex I countries



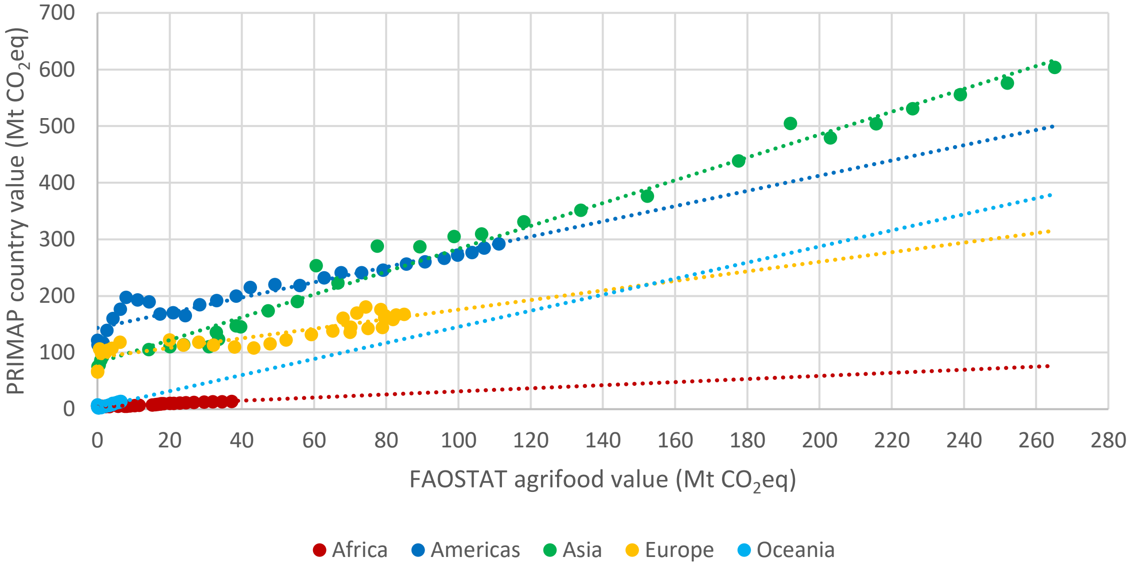
Source: Authors' own elaboration.

When comparing the trends across time series, the correlation statistics indicate a strong positive correlation between the FAO agrifood systems emissions estimates and the other two F-gas emissions estimates. In particular, the correlation between FAO agrifood systems emissions and PRIMAP country total F-gas emissions trends (not food-specific and with global coverage) is 0.99 at the global level. This high correlation coefficient suggests that the FAO agrifood emissions estimates are consistent with an established global database, and therefore its trends can be considered a valid source of information at the aggregate level. The correlation between FAO agrifood systems emissions and UNFCCC Annex I countries (referring to countries that report data to the UNFCCC) emissions is 0.97 at the global level, even though the UNFCCC global aggregate comprises only 43 countries. Interestingly, the growth in F-gas emissions is more modest in the past five years in UNFCCC Annex I countries, even though the global total continues to increase rapidly. This may indicate that F-gas emissions are beginning to be mitigated in industrialized economies, which would be in line with the Kigali Amendment to the Montreal Protocol. At the same time, as both the FAOSTAT and PRIMAP global estimates continue to grow quickly, it may indicate that the growth of F-gas emissions in non-Annex I countries more than makes up for the mitigated emissions in Annex I countries. Overall, the high correlation between the FAO agrifood systems emissions estimates and the other two emissions estimates provide strong evidence for the validity of the FAO data at the global aggregate level.

## 5.2 Regional validation

The FAOSTAT F-gas emissions data at the regional level were validated using the PRIMAP database. UNFCCC data are not used due to the lack of regional coverage. The annual PRIMAP data is plotted on the vertical axis and the annual FAOSTAT data is plotted on the horizontal axis. The correlation is for regional values across both time series. The results are shown in Figure 2.

**Figure 2.** Comparison of the PRIMAP country estimates with the FAO agrifood systems F-gas emissions estimates by region



Source: Authors' own elaboration.

In Table 3, the R-squared values for each region are relatively high (ranging from 0.78 to 0.99), suggesting that the methodology does well at capturing variance in the data for each region. In this table, given the high R-squared values and low p-values for each regional comparison, the methodology or being tested is likely to be valid and generalizable to the populations represented by the different regions.

**Table 3.** Statistical significance and explanatory value of FAOSTAT agrifood systems emission data against PRIMAP total sectoral F-gas emissions for regional aggregates (1990–2020)

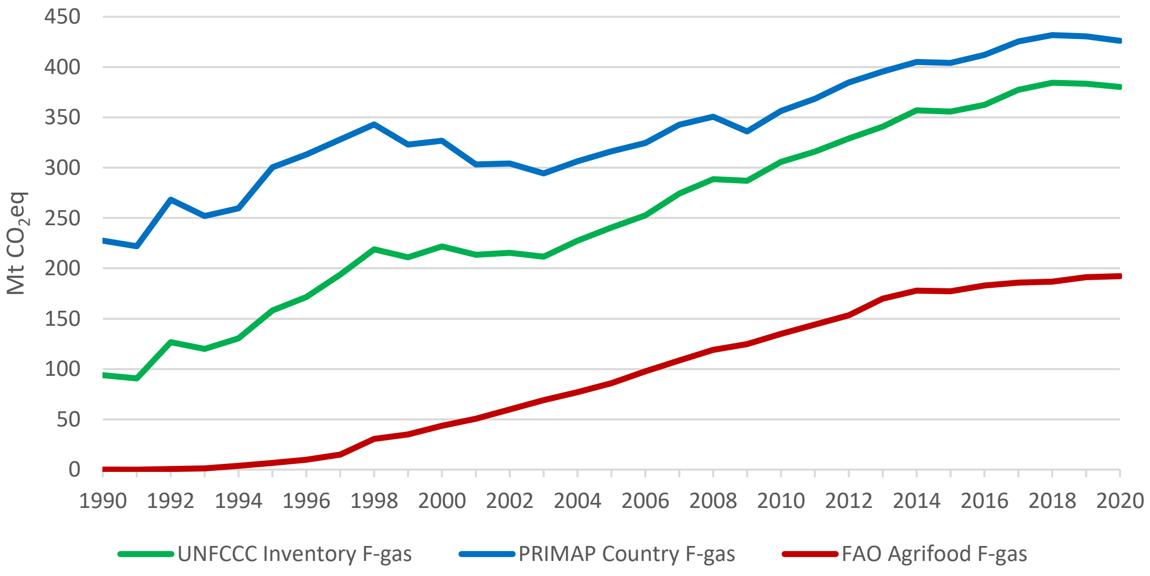
| Region | R-squared | p-value |
|---|---|---|
| Africa | 0.96 | < 0.0001 |
| Americas | 0.90 | < 0.0001 |
| Asia | 0.99 | < 0.0001 |
| Europe | 0.78 | < 0.0001 |
| Oceania | 0.81 | < 0.0001 |

Source: Authors' own elaboration.

## 5.3 Validation without imputation of missing countries

As previously mentioned, the country-level data provided in the UNFCCC inventory cover only 43 countries, primarily in industrialized economies. When limiting the analysis to these 43 countries only, the FAOSTAT agrifood system data developed by this methodology follow the country-level HFC emissions quite well, with variations in the time series data being smoothed out due the methodology described above. From this analysis, it appears that HFC emissions have indeed started to decline in industrialized economies after peaking in 2018, although the FAOSTAT emissions estimates indicate an emissions plateau rather than a decrease.

**Figure 3.** F-gas emissions estimates by source, for the 43 countries covered by the UNFCCC inventory

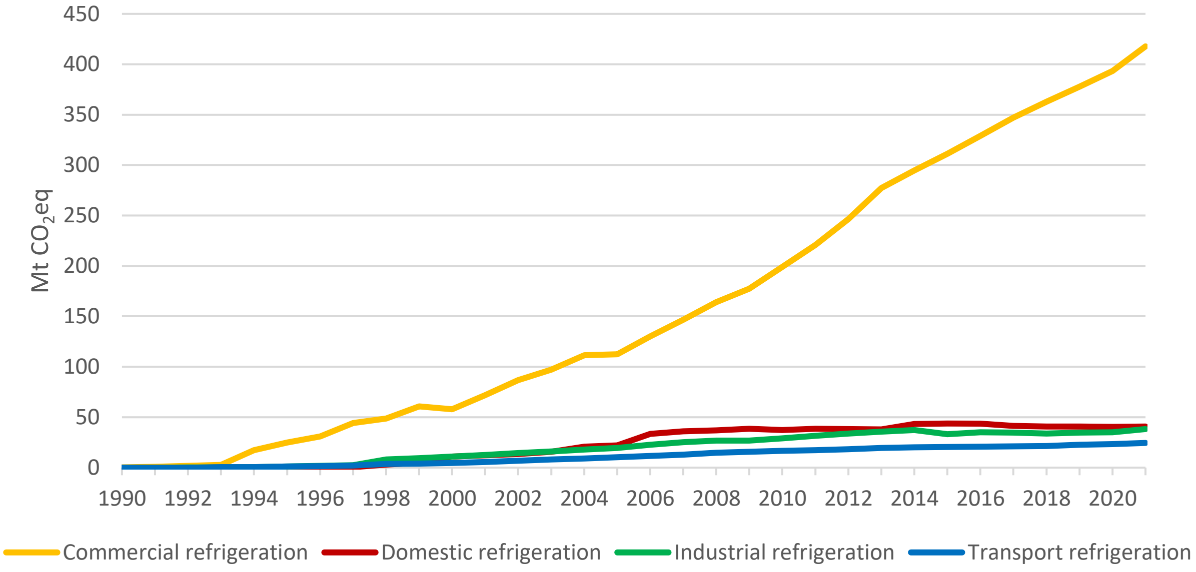


Source: Authors' own elaboration.

## 5.4 Cold chain steps validation

From 2000 to 2021, as the use of HFCs became widespread, F-gas emissions from agrifood systems cold chains increased across all cold chain steps. At the same time, it is also the case that emissions from chlorofluorocarbon (CFCs) decreased, as they have been gradually phased out via the Montreal Protocol due to their part in ozone depletion. Commercial refrigeration experienced an increase of 621 percent from 58 Mt $CO_2$eq to 418 Mt $CO_2$eq. Domestic refrigeration grew from 11 Mt $CO_2$eq in 2000 to 41 Mt $CO_2$eq in 2021, while industrial refrigeration expanded from 11 Mt $CO_2$eq to 38 Mt $CO_2$eq, and transport refrigeration increased from 5 Mt $CO_2$eq to 25 Mt $CO_2$eq. This is consistent with the results from the methodology adopted by the IIR, where the emissions estimates indicated that food retail has by far the highest carbon footprint from F-gas emissions, followed by domestic, industrial and transport refrigeration emissions.

**Figure 4.** Agrifood systems F-gas emissions by component



Source: Authors' own elaboration.

# 6 Conclusion

The methodology presented in this paper provides a valuable addition to the existing approaches for estimating greenhouse gas emissions from agrifood systems. By focusing on F-gases from refrigeration systems in the agrifood system cold chain, this study addresses a critical aspect of agrifood emissions that has been less explored in previous research. The proposed methodology enables the creation of a comprehensive database of F-gas emissions in the agrifood system, covering the period from 1990 to 2021, with global coverage and country-specific data. The resulting estimates are consistent with established global databases, lending credibility to their use in future research and policymaking.

This new methodology offers several advantages over previous approaches. By incorporating a detailed breakdown of the cold chain steps and specific F-gases, it provides a more granular and accurate estimation of the emissions associated with food refrigeration. Additionally, the imputation of missing data enables a more complete picture of global agrifood system emissions.

The availability of reliable, detailed emissions data is essential for driving effective climate policies. As highlighted in the original text, promoting the development and adoption of low-GWP refrigerant technologies is crucial to mitigate the climate impact of the cold chain industry. By providing a more accurate and comprehensive view of F-gas emissions in the agrifood system, this methodology can support evidence-based decision-making, ensuring that the global community can strike a balance between food security and climate change mitigation. In conclusion, this methodology not only enhances our understanding of F-gas emissions in the agrifood system but also contributes to the development of more sustainable and resilient agrifood systems in the future.

# 7 References

Bjønness, K.L., Gustafsson, T., Ishikawa, J. & Maione, M. 2019. Chapter 7: Emissions of Fluorinated Substitutes for Ozone Depleting Substances. In: *Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/3_Volume3/19R_V3_Ch07_ODS_Substitutes.pdf

Center for Climate and Energy Solutions (C2ES). 2019. Short-lived Climate Pollutants. In: *C2ES*. Arlington, USA. Cited March 2023. https://www.c2es.org/content/short-lived-climate-pollutants/

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., & Leip, A. 2021a. Food systems are responsible for a third of global anthropogenic GHG emissions. *Nature Food*, 1–12. https://doi.org/10.1038/s43016-021-00225-9

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N. & Leip, A. 2021b. EDGAR-FOOD data. Cited March 2023. doi:10.6084/m9.figshare.13476666

Crippa, M., Guizzardi, D., Schaaf, E., Solazzo, E., Muntean, M., Monforti-Ferrario, F., Olivier, J.G.J. & Vignati, E. 2021c. Emissions Database for Global Atmospheric Research (EDGAR) v6.0. In: *European Commission*. Brussels. Cited March 2023. https://edgar.jrc.ec.europa.eu/index.php/dataset_ghg60

Devotta S. & Sicars, S. 2005. Chapter 4: Refrigeration. In: B. Metz, L. Kuijpers, S. Solomon, S.O. Andersen, O. Davidson, J. Pons, D. de Jager, T. Kestin, M. Manning &, L. Meyer, eds. *IPCC/TEAP Special Report: Safeguarding the Ozone Layer and the Global Climate System.* Cambridge, UK, Cambridge University Press. https://archive.ipcc.ch/pdf/special-reports/sroc/sroc04.pdf

Domanski, P. A., McLinden, M. O. & Bell, I. H. 2018. *Low-GWP Alternative Refrigerant Blends for HFC-134a*. Gaithersburg, USA, National Institute of Standards and Technology. https://doi.org/10.6028/NIST.TN.2014

Duarte, M. V., Pires, L. C., Silva, P. D. & Gaspar, P. D. 2017. Current and Future Trends of Refrigerants Development. In: *Agri-Food Supply Chain Management: Breakthroughs in Research and Practice* (pp. 474-524). IGI Global.

Dawson, C. J. & Hilton, J. 2011. Fertiliser availability in a resource-limited world: Production and recycling of nitrogen and phosphorus. *Food Policy*, 36, S14–S22. https://doi.org/10.1016/j.foodpol.2010.11.012

EIA (Energy Information Administration). 2021. International energy outlook 2021. In: *EIA*. Washington, DC, USA. Cited March 2023. https://www.eia.gov/outlooks/ieo/

Environmental Investigation Agency. 2019. Leaking Havoc: Exposing Your Supermarket's Invisible Climate Pollution. In: *Climate-friendly supermarkets*. Washington, DC, USA. Cited March 2023. https://www.climatefriendlysupermarkets.org/leaking-havoc

FAO. 2019. *The State of Food and Agriculture 2019. Moving forward on food loss and waste reduction*. Rome. https://doi.org/10.4060/ca6030en

FAO. 2021a. *FAOSTAT domain Emissions shares. Methodological note, release November 2022*. Rome. https://fenixservices.fao.org/faostat/static/documents/EM/EM_e.pdf

FAO. 2021b. *Emissions from Agriculture and Forest Land. Global, Regional and Country Statistics, 1990-2019*. FAOSTAT Analytical Brief Series No 25. Rome. http://www.fao.org/3/cb5293en/cb5293en.pdf

FAO. 2021c. *The State of Food and Agriculture 2021. Making agrifood systems more resilient to shocks and stresses*. Rome. https://doi.org/10.4060/cb4476en

FAO. 2022. FAOSTAT: Emissions totals. In: *FAO*. Rome. Cited March 2023. https://www.fao.org/faostat/en/#data/GT

Flammini, A., Pan, X., Tubiello, F.N., Qiu, S.Y., Rocha Souza, L., Quadrelli, R., Bracco, S., Benoit, P. & Sims, R. 2022. Emissions of greenhouse gases from energy use in agriculture, forestry and fisheries: 1970–2019. *Earth System Science Data Discussions*. https://essd.copernicus.org/preprints/essd-2021-262/

Flammini, A., Adzmir, H., Karl, K. & Tubiello, F. 2023a. *Methods for estimating greenhouse gas emissions from food systems – Part V: Household food consumption*. FAO Statistics Working Paper Series, No. 22−23. Rome, FAO. https://doi.org/10.4060/cc3812en

Flammini, A., Adzmir, H., Karl, K. & Tubiello, F. 2023b. Quantifying Greenhouse Gas Emissions from Woodfuel used in Households. *Earth System Science Data Discussions*, 1–17. https://doi.org/10.5194/essd-2022-390

Foster, A., Brown, T. and Evans, J., 2023. Carbon emissions from refrigeration used in the UK food industry. *International Journal of Refrigeration*.

Göransson, M., Nilsson, F. & Jevinger, Å. 2018. Temperature performance and food shelf-life accuracy in cold food supply chains – Insights from multiple field studies. *Food Control*, *86*, 332–341. https://doi.org/10.1016/j.foodcont.2017.10.029

Heredia-Aricapa, Y., Belman-Flores, J. M., Mota-Babiloni, A., Serrano-Arellano, J. & García-Pabón, J.J. 2020. Overview of low GWP mixtures for the replacement of HFC refrigerants: R134a, R404A and R410A. *International Journal of Refrigeration*, 111, 113–123. https://doi.org/10.1016/j.ijrefrig.2019.11.012

International Institute of Refrigeration. 2021. The Carbon Footprint of the Cold Chain, 7th Informatory Note on Refrigeration and Food. In: *IIR*. Paris. Cited March 2023. https://iifiir.org/en/fridoc/the-carbon-footprint-of-the-cold-chain-7-lt-sup-gt-th-lt-sup-gt-informatory-143457

International Institute of Refrigeration, United Nations Environment Programme, Ozone Action, UN Environment. 2018. Cold Chain Technology Brief: Transport Refrigeration. In: *IIR*. Paris. Cited March 2023. https://iifiir.org/en/fridoc/cold-chain-technology-brief-transport-refrigeration-142037

International Energy Agency. 2021. *India Energy Outlook 2021*. Paris. https://iea.blob.core.windows.net/assets/1de6d91e-e23f-4e02-b1fb-51fdd6283b22/India_Energy_Outlook_2021.pdf

IRENA and FAO. 2021. *Renewable energy for agri-food systems – Towards the Sustainable Development Goals and the Paris Agreement*. Abu Dhabi and Rome. https://doi.org/10.4060/cb7433en

IPCC. 2014. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, IPCC. https://www.ipcc.ch/site/assets/uploads/2018/02/SYR_AR5_FINAL_full.pdf

Karl, K. & Tubiello, F.N. 2021. *Methods for estimating greenhouse gas emissions from food systems. Part I: domestic food transport*. FAO Statistics Working Paper 21-27. Rome, FAO. https://doi.org/10.4060/cb6754en

Karl, K. & Tubiello, F.N. 2021. *Methods for estimating greenhouse gas emissions from food systems. Part II: waste disposal*. FAO Statistics Working Paper 21-28. Rome, FAO. https://doi.org/10.4060/cb7028en

Kummu, M., Kinnunen, P., Lehikoinen, E., Porkka, M., Queiroz, C., Röös, E., Troell, M. & Weil, C. 2020. Interplay of trade and food system resilience: Gains on supply diversity over time at risks of trade-induced shocks. *Global Food Security*, 24, 100360. https://doi.org/10.1016/j.gfs.2020.100360

Pambudi, N., Sarifudin, A., Gandidi, I. & Romadhon, R. 2022. Vaccine cold chain management and cold storage technology to address the challenges of vaccination programs. *Energy Reports*, 8, 955-972. https://www.sciencedirect.com/science/article/pii/S2352484721014785

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B.L., Lassaletta, L., de Vries, W., Vermeulen, S.J., Herrero, M., Carlson, K.M., Jonell, M., Troell, M., DeClerck, F., Gordon, L.J., Zurayk, R., Scarborough, P., Rayner, M., Loken, B., Fanzo, J., Godfray, H.C.J., Tilman, D., Rockström, J. & Willett, W. 2018. Options for keeping the food system within environmental limits. *Nature*, 562(7728), 519-525. https://doi.org/10.1038/s41586-018-0594-0

Srikaummun, N., Wongsapai, W., Damrongsak, D., Thepsakul, W., Ritkrekkrai, C., Bunchuaidee, R., Tridech, N. & Juprasert, P. 2021. Greenhouse gas mitigation and electricity saving potential from replacing refrigerants in Thai refrigerator. *Energy Reports*, 7 (Supplement 5), 98-104. https://doi.org/10.1016/j.egyr.2021.07.138

Tubiello, F.N. 2019. Greenhouse Gas Emissions Due to Agriculture. In: P. Ferranti, E. M. Berry & J. R. Anderson, eds. *Encyclopedia of Food Security and Sustainability*, pp. 196–205. Elsevier. https://doi.org/10.1016/B978-0-08-100596-5.21996-3

Tubiello, F. N., Rosenzweig, C., Conchedda, G., Karl, K., Gütschow, J., Xueyao, P., Obli-Laryea, G., Wanner, N., Qiu, S.Y., De Barros, J. & Flammini, A. 2021. Greenhouse gas emissions from food systems: building the evidence base. *Environmental Research Letters*, 16(6), 065007.

Tubiello, F.N., Karl, K., Flammini, A., Gütschow, J., Obli-Laryea, G., Conchedda, G., Pan, X., Qi, S.Y., Halldórudóttir Heiðarsdóttir, H., Wanner, N., Quadrelli, R., Rocha Souza, L., Benoit, P., Hayek, M., Sandalow, D., Mencos Contreras, E., Rosenzweig, C., Rosero Moncayo, J., Conforti, P. & Torero, M. 2022. Pre- and post-production processes increasingly dominate greenhouse gas emissions from agri-food systems. *Earth System Science Data*, 14(4), 1795–1809. https://doi.org/10.5194/essd-14-1795-2022

UNDP. 2020. *Human development report 2020. The Next Frontier: Human Development and the Anthropocene*. New York, USA. https://hdr.undp.org/system/files/documents//hdr2020pdf.pdf

UNEP. 2022. *Cooling emissions and policy synthesis report*. Nairobi. https://wedocs.unep.org/bitstream/handle/20.500.11822/33094/CoolRep.pdf

Velders, G. J., Fahey, D. W., Daniel, J. S., McFarland, M. & Andersen, S. O. 2009. The large contribution of projected HFC emissions to future climate forcing. Proceedings of the National Academy of Sciences, 106(27), 10949-1095

**Contact:**

Statistics Division – Economic and Social Development
FAO-statistics@fao.org
www.fao.org/food-agriculture-statistics/resources/publications/working-papers/en/

**Food and Agriculture Organization of the United Nations**
Rome, Italy

ISBN 978-92-5-137821-2

9 789251 378212

CC5403EN/1/04.23