The greenhouse gas emissions of pharmaceutical consumption and production: an input–output analysis over time and across global supply chains

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Summary

Background **Health care substantially contributes to global greenhouse gas emissions, but for pharmaceuticals, this is mostly understood through case studies of individual medicines. Using newly compiled international databases, we aimed to analyse global greenhouse gas emissions from pharmaceutical consumption and production over time and across supply chains.**

Methods **We quantified the pharmaceutical greenhouse gas footprint across 77 regions from 1995 to 2019 using environmentally extended multi-regional input–output (EE-MRIO) analysis, then conducted structural decomposition analysis to assess key drivers. To identify producers' full supply chain emission responsibility and mitigation opportunities, we performed structural path analysis and assessed scope 1–3 emissions, supported by a Sankey diagram visualisation. Our analysis was based on data from the EE-MRIO database developed by the Organisation for Economic Co-operation and Development (Inter-Country Input–Output tables 2023) and validated using the EE-MRIO database developed by Eurostat (FIGARO-2024).**

Findings **From 1995 to 2019, the global pharmaceutical greenhouse gas footprint grew by 77%. This increase was primarily driven by rising pharmaceutical final expenditure, especially in China, and efficiency gains stalling after 2008. High-income countries contributed, on average, a nine-times to ten-times higher pharmaceutical greenhouse gas footprint per capita than lower-middle-income countries in 1995–2019. Supply chain emissions varied substantially among major suppliers in intensity, overseas displacement, and upstream effects.**

Interpretation **Greenhouse gas emissions related to pharmaceuticals have risen substantially and are likely to continue to rise without concerted and coordinated action. Pharmacies and researchers should investigate sources of unnecessary pharmaceutical use and waste, the industry should improve supply chain efficiency, governments should promote pharmaceutical waste reduction programmes, and international organisations must support global mitigation efforts, especially given the growing importance of scope 3 emissions and international outsourcing.**

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Introduction

Climate change is increasingly recognised as one of the largest health challenges of the 21st century.[1,2] Its impacts—such as droughts, storms, wildfires, and rising sea levels—threaten key environmental and social determinants of health, including clean air, safe water, and sustainable food systems.[3] Additional consequences include extended allergy seasons, heat stress, and more water-borne and vector-borne diseases.[4,5] Vulnerable populations, such as lower-income communities, women, children, older people, migrants, and those with pre-existing health conditions, face disproportionate risks.[6] Addressing these challenges requires a comprehensive health response.[2] To date, 93 countries have committed to developing sustainable, low-carbon health systems.[7]

The growing awareness of climate-related health-care risks, along with increased emission mitigation commitments, has spurred investigations into the greenhouse gas footprint of the health-care sector at both national[8–13] and global[14,15] levels. Unlike conventional greenhouse gas accounting, which only considers emissions directly released from sources owned by health-care providers, the footprint method adopts a consumption-based approach. This method attributes both direct and indirect emissions throughout health-care supply chains to the final beneficiaries, because their expenditure ultimately drives these emissions.[16] Using an environmentally extended multi-regional input–output (EE-MRIO) approach, the health-care sector's greenhouse gas footprint has been shown to account for 5% of global greenhouse gas emissions (2·4 Gt CO_2 equivalent [CO_2e] in 2015),[14] which is substantially more than, for example, the aluminium industry's direct emissions (about 1 Gt CO_2e in 2015).[17]

Although several national-level studies have highlighted pharmaceutical consumption as a major

Research in context

Evidence before this study

Although the environmental impact of health care has been assessed in some previous studies, the contribution of pharmaceuticals remains underexplored. We searched Web of Science and PubMed up to Sept 1, 2024, for results in English using the keywords "pharmaceutical", "medicine", and "footprint" in titles and abstracts. Most previous studies identified by this search have focused on a specific set of medicines, often relying on theoretical models due to data constraints. One study found that using company reports would greatly underestimate the emissions along global pharmaceutical supply chains, as captured by an environmentally extended multi-regional input–output (EE-MRIO) analysis, a macroeconomic approach. Furthermore, in previous global and national EE-MRIO studies, pharmaceuticals are often indistinguishable from chemicals or health care due to the lack of high-quality international data. To our knowledge, no study has examined the global evolution of greenhouse gas emissions related to pharmaceuticals over time and across supply chains.

Added value of this study

Our study advances research in four key areas. First, using a recently released dataset from the Organisation for Economic Co-operation and Development, we present the first global greenhouse gas footprint time series for pharmaceutical consumption and production. The dataset separates pharmaceuticals from chemicals and health care, and disaggregates previous groups of lower-middle-income and upper-middle-income countries (eg, Kazakhstan, Belarus, and Senegal), enabling deeper insights into global health-care inequalities. We find a 77% increase in global pharmaceutical greenhouse gas footprint from 1995 to 2019, with high-income countries persistently contributing, on average, nine-times to ten-times more per capita than lower-middle-income countries. Second, our analysis identifies rising pharmaceutical expenditures as the primary driver of the global footprint increase, with efficiency gains offsetting half of the increase. However, crucially, we highlight that progress has stalled since 2008. Third, we reveal the growing role of supply chains and international outsourcing in pharmaceutical producers' emission responsibility, supported by a novel supply chain visualisation. Finally, leveraging two recently released datasets from authoritative international bodies, we validate that pharmaceuticals have substantially higher emission intensities than health-care services, and together they contribute about 3% of the global greenhouse gas footprint.

Implications of all the available evidence

A comprehensive analysis of greenhouse gas emissions related to pharmaceuticals, from both consumption and production perspectives over time, has been lacking but is essential for effective mitigation. Our study addresses this gap, highlighting the urgent need for multi-stakeholder actions to curb the sector's rapidly growing greenhouse gas footprint and address cross-country disparities. Governments can help reduce preventable pharmaceutical wastes and overuse by initiating programmes for optimised prescription practices, right-sized packaging, lifestyle counselling, and expanded take-back options, alongside ensuring quality control and regulatory support. The pharmaceutical industry must enhance production efficiency, decarbonise supply chains, and improve transparency to pinpoint emission hotspots. More research is needed to understand country-specific drivers and waste management strategies, and international collaboration can help mitigate the large variation in per-capita emissions among high-income countries. Lastly, international organisations must improve data granularity for pharmaceutical products and low-income regions, supporting accurate assessments and equitable health-care access.

contributor to the greenhouse gas footprint of health care, with estimates ranging from 19% to 55%,[8–13] a global assessment is lacking due to previous data constraints. Scaling up the national estimates to a global level is not straightforward, because these studies primarily focus on higher-income countries, often have methodological inconsistencies, and might overlook the displacement of a substantial portion of each country's pharmaceutical greenhouse gas footprint through embodied emissions in international trade. These issues highlight the necessity for a global approach.

In terms of production, the pharmaceutical industry's emission responsibility and mitigation opportunities are also underexplored. Most studies focus on a limited set of medicines.[18] One notable study assessed scope 1 emissions (those directly generated by the industry) and scope 2 emissions (associated with the industry's energy purchases) based on reports from the top 15 global pharmaceutical companies.[19] However, a follow-up analysis showed that the combined scope 1 and 2 emissions were 87% larger when using a macroeconomic approach.[20] An initial assessment of the industry's scope 3 emissions, which include all indirect emissions not covered by scope 2, showed that they are 4·3-times greater than the scope 1 and 2 emissions combined.[20]

Here, we present a comprehensive global analysis of the greenhouse gas emissions from pharmaceutical consumption and production across countries and over time, revealing key temporal and spatial patterns to inform global trends and region-specific mitigation strategies. From a consumption perspective, we develop the first global time series of total and per-capita pharmaceutical greenhouse gas footprints for 77 regions from 1995 to 2019 and analyse the key drivers of these trends. From a production perspective, we assess and visualise supply chain emissions of top pharmaceutical-producing countries, identifying hotspots and critical sectoral linkages for effective mitigation. We also provide a novel assessment of scope 1–3 emissions across all regions and examine how their emission responsibilities have evolved both spatially and over time. Our global estimates have been validated using two authoritative global databases recently released by the Organisation for Economic Co-operation and Development (OECD)[21] and Eurostat (the statistical office of the EU).[22]

Methods

Study design

We conducted an EE-MRIO analysis to assess greenhouse gas emissions of pharmaceutical consumption across 76 countries, as well as an additional region encompassing the rest of the world, from 1995 to 2019. We then employed structural decomposition analysis to identify key drivers of the global pharmaceutical greenhouse gas footprint. In terms of production, to elucidate emission responsibilities and mitigation opportunities across full supply chains, we performed structural path analysis and assessed scope 1–3 emissions. Finally, we validated the data using the EE-MRIO database developed by Eurostat (FIGARO-2024).

EE-MRIO data and footprint assessment

We conducted our primary analysis using Inter-Country Input–Output tables (ICIO)-2023, the latest EE-MRIO database from the OECD.[21] It includes data—such as emission accounts aggregating eight types of greenhouse gas (appendix p 2)—up to July, 2024,[23] and improves coverage of previously aggregated lower-middle-income or higher-middle-income countries (eg, Kazakhstan, Belarus, and Senegal), making our global model more inclusive. Although the database spans 1995–2020, we focused on 1995–2019 to exclude the year affected by COVID-19 (2020) and avoid distortion in trend analysis. ICIO details 45 economic sectors: "Pharmaceuticals, medicinal chemical and botanical products" represents pharmaceuticals and "Human health and social work activities" represents health-care services (appendix pp 2–3).

We assessed the pharmaceutical greenhouse gas footprint by region and year using the Leontief demand-driven model, a well established consumption-based EE-MRIO method that attributes all supply chain emissions to final pharmaceutical expenditures, which ultimately drive them (appendix p 1). Our calculations use annual accounts of emissions, final expenditures, and interindustry transactions, ensuring that interannual price changes do not affect trends in annual pharmaceutical greenhouse gas footprints assessed in physical units. The per-capita estimates were based on World Bank population data,[24] and regions were grouped by income level following the World Bank classification (appendix pp 3–5).[25]

Analysing temporal trends and emission drivers

We applied structural decomposition analysis, a widely used method for analysing macro-environmental changes,[26–29] to identify key drivers of global pharmaceutical greenhouse gas footprints. Using the ICIO-2023 time series in previous year prices (pyp) and current year prices (cyp), we followed the approach detailed by Hoekstra and colleagues.[27] Global emission changes (Δq) were attributed to three key effects (D): a technology effect from changes in direct emission intensity (D_f) and production recipe (D_{A*}), a sourcing effect due to changes in international sourcing of intermediate (D_C) and finished (D_F) products, and a consumption effect (D_y) from changing final expenditure. Global emission changes were calculated as: $\Delta q = D_f + D_{A*} + D_C + D_F + D_y$.

To assess the temporal trends in emission intensity (tonnes CO_2e per million US$) of global pharmaceutical production, we calculated two global average emission intensities for each year t. The global direct emission intensity ($f^{cyp}_{Pharm,t}$) was derived by dividing the total direct pharmaceutical emissions across all 77 regions ($\sum_{i=1}^{77} F_{\mathrm{Pharm},i,t}$) by their total gross output of pharmaceuticals ($\sum_{i=1}^{77} x^{cyp}_{Pharm,i,t}$) in cyp. The global total emission intensity ($m^{cyp}_{Pharm,t}$), which includes direct and indirect emissions (full supply chain), was calculated by dividing the global pharmaceutical greenhouse gas footprint (q^{cyp}) by the total final expenditure on pharmaceuticals ($\sum_{i=1}^{77} y^{cyp}_{Pharm,i,t}$).

We then corrected the values for inflation using the pyp and cyp time series, and expressed them in constant 2019 prices. The inflation rate, $\pi_{Pharm,t}$, was calculated as:

See Online for appendix

$$\pi_{Pharm,t} = \frac{\sum_{i=1}^{77} x^{cyp}_{Pharm,i,t} - \sum_{i=1}^{77} x^{pyp}_{Pharm,it}}{\sum_{i=1}^{77} x^{pyp}_{Pharm,it}}.$$

$\pi_{Pharm,k}$ was used to adjust $f_{\mathrm{Pharm},t}$ to constant 2019 prices (k ranges from t+1 to 2019):

$$f^{2019}_{\mathrm{Pharm},t} = f^{cyp}_{Pharm,t} \times \prod_{k=t+1}^{2019} (1 + \pi_{Pharm,k}).$$

$\pi_{Pharm,k}$ was also applied to adjust $m^{cyp}_{Pharm,t}$ to $m^{2019}_{\mathrm{Pharm},t}$.

Production supply chain analysis

We used structural path analysis[30,31] to trace the pharmaceutical industry's greenhouse gas emissions across its supply chain, distinguishing between the industry's direct emissions and indirect emissions generated by industries at upstream steps in the supply chain (ie, production layers, PL1 to PL5). For example, emissions from chemicals directly used in pharmaceutical production are indirect emissions at PL1, and emissions from the electricity directly used to produce those chemicals are counted at PL2. We visualised these data in Sankey diagrams and for clarity we aggregated the 45 industries into eight sectors and included emission flows that accounted for less than 0·1% of the pharmaceutical industry's total supply chain emissions under "other industries".

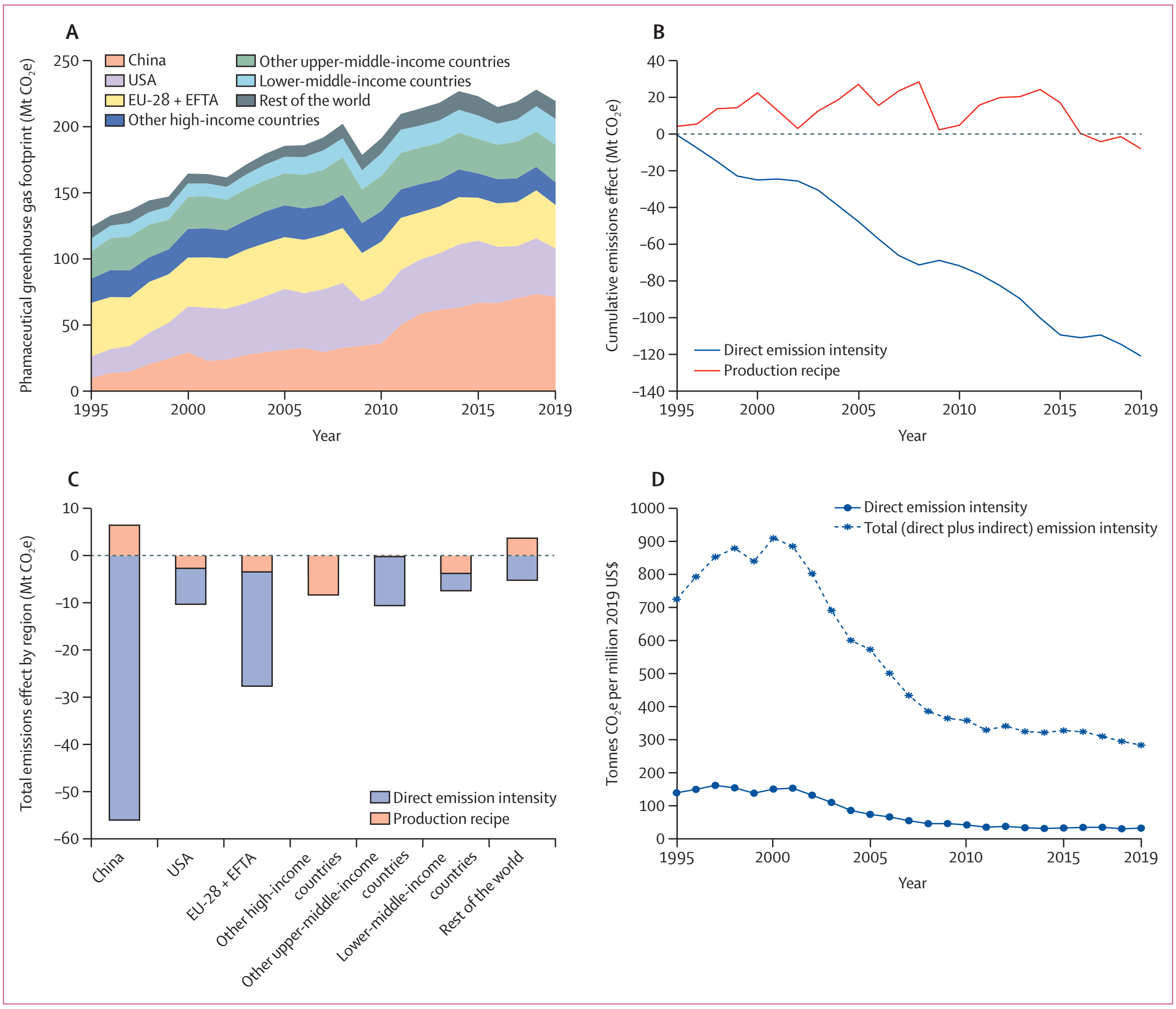

Figure 1: **Trends and drivers of the global pharmaceutical greenhouse gas footprint from 1995 to 2019**
(A) Global pharmaceutical greenhouse gas footprint. Region classification is detailed in the appendix (pp 3–5). (B, C) Decomposition of the cumulative technology effects into two sources—change in direct emission intensity and change in production recipe—over time (B) and by region (C). (D) Trends of global average direct and total emission intensities of pharmaceutical production. EFTA=European Free Trade Association.

We calculated scope 1–3 greenhouse gas emissions for each country's pharmaceutical industry following the economy-wide approach of Hertwich and Wood (appendix pp 1–2).[16] We assessed current supply chain emission responsibility based on the 2019 results, focusing on the shares of scopes 1–3 in the total emissions and the proportion of emissions displaced overseas. We then analysed changes by comparing results from 1995 to 2019. Due to data limitations, we did not adjust for the greenhouse gas emissions associated with pharmaceutical machinery and infrastructure build-up.

Uncertainty analysis and validation

Validation in EE-MRIO analysis is uncommon due to the extensive data involved and the absence of standardised data processing methods, which have only recently emerged with contributions from international organisations. We validated our results using the FIGARO-2024 EE-MRIO database from Eurostat,[22] focusing on key global estimates, including temporal trends and the relative greenhouse gas emissions of pharmaceuticals and health-care services.

Role of the funding source

The funder had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

The global greenhouse gas footprint of the final expenditure on pharmaceuticals has grown by 77%, from 124·2 Mt CO_2e in 1995 to 219·6 Mt CO_2e in 2019 (figure 1A). This increase was substantially driven by the USA and mainland China. The combined share of the global pharmaceutical greenhouse gas footprint for these two countries increased from 21% in 1995 to 49% in 2019. China experienced the largest absolute increase from 9·6 Mt CO_2e to 71·2 Mt CO_2e. By contrast, the 17 lower-middle-income countries specified in our dataset, representing 36% of the global population in 2019, contributed only 9% of the global pharmaceutical greenhouse gas footprint. Among them, India, despite having a population similar to China in 2019, accounted for just 4% of the global pharmaceutical greenhouse gas footprint. Although the overall global greenhouse gas footprint increased, 17 countries had considerable reductions (of at least 20%) from 1995 to 2019, mostly in Europe. Overall, Europe, including all EU-28 and three European Free Trade Association countries (Iceland, Norway, and Switzerland), had a pharmaceutical footprint reduction from 40·6 Mt CO_2e to 33·0 Mt CO_2e.

The main driver behind the global pharmaceutical footprint increase is the rise in pharmaceutical final expenditure, accounting for 193% (231 Mt CO_2e) of the total footprint change from 1995 to 2019 (table 1). Pharmaceutical expenditure growth in upper-middle-income countries contributed 118% to the global change, with China alone accounting for 102%. By contrast, lower-middle-income countries contributed to only 17% of the global footprint change.

Technology effects were crucial in reducing the global pharmaceutical footprint, contributing to a reduction of 129 Mt CO_2e (–107%) from 1995 to 2019, but they did not fully offset the emission rise from increased final expenditures. Most of the reductions (121 Mt CO_2e) came from improved direct emission intensities of production, including pharmaceuticals and other activities involved in the pharmaceutical supply chains (figure 1B, C). Of these, 56 Mt CO_2e came from emission intensity reduction in China, particularly after 2011 (appendix p 5), followed by 28 Mt CO_2e from Europe, and 10 Mt CO_2e from the USA. Focusing on the pharmaceutical industry's emission intensity, both direct and total, a slowing in reductions from 2008 onwards is notable, despite an overall decline (figure 1D).

Per capita, pharmaceutical greenhouse gas footprints vary widely between countries and income groups (figure 2A, B). High-income countries have the highest per-capita emissions, with notable variations within the group. Between 1995 and 2019, the average per-capita footprint of high-income countries saw minimal change, slightly increasing from 71 kg CO_2e to 73 kg CO_2e. The average of lower-middle-income countries went from 7 kg CO_2e to 8 kg CO_2e per capita, maintaining a large gap in which the average per-capita footprint was nine-times to ten-times higher in high-income countries than in lower-middle-income countries. Among the 77 regions analysed, per-capita footprint changes over 1995 to 2019 varied: 25 countries, mostly in Europe (14 countries), had a decrease of at least 20%, whereas 30 countries, including the USA, China, eight European countries, and 13 lower-middle-income countries, had increases of 20% or more. China's per-capita footprint remained less than half that of the USA by 2019, despite surpassing the USA in terms of total pharmaceutical greenhouse gas footprint.

	Technology (%)	Sourcing (%)	Consumption (%)	Total (%)
China	–41%	–2%	102%	58%
USA	–11%	10%	29%	28%
EU-28 plus European Free Trade Association	–26%	2%	23%	–1%
Other high-income countries	–10%	1%	6%	–3%
Other upper-middle-income countries	–9%	1%	15%	7%
Other lower-middle-income countries	–9%	0%	17%	8%
Rest of the world	–1%	1%	1%	1%
Total	–107%	14%	193%	100%

Technology effects are due to changes in emission intensities and production recipes. Sourcing effects are from changes in sourcing patterns for intermediate inputs and final expenditure. Consumption effects are due to changes in pharmaceutical expenditure. The effects are expressed as percentages of the total global change. Percentages might not add to totals due to rounding.

Table 1: **Decomposition of the global pharmaceutical footprint changes into three primary effects**

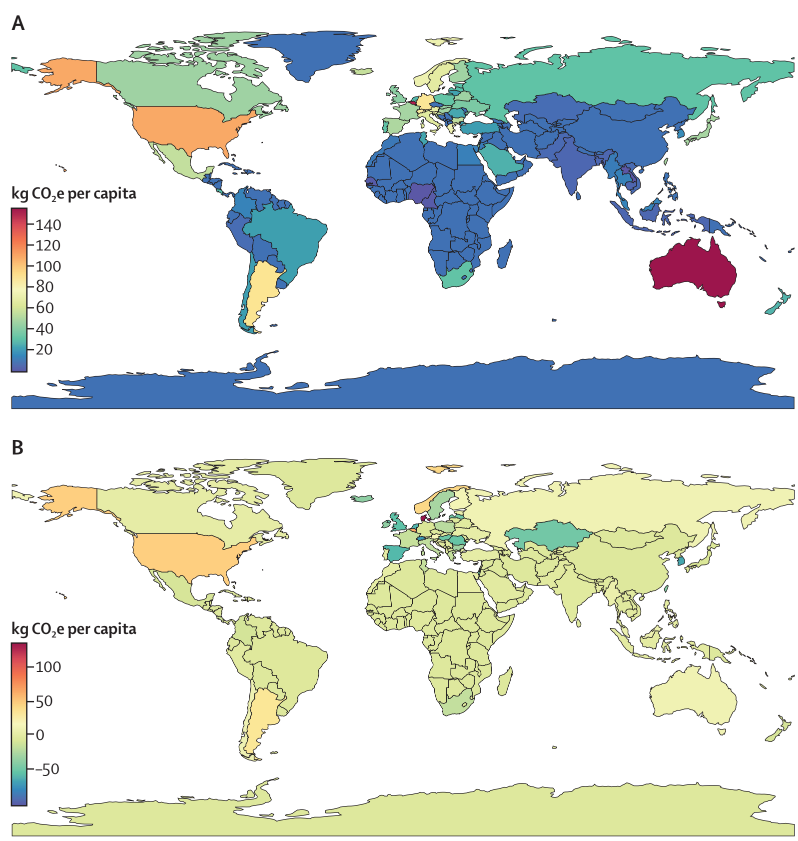

Figure 2: **Per-capita pharmaceutical greenhouse gas footprint across countries**
(A) Per-capita greenhouse gas footprint in 2019. (B) Absolute change in per-capita greenhouse gas footprint between 1995 and 2019. Countries not specified in the ICIO-2023 database are plotted with the per-capita estimates of the aggregated rest of the world region. For better visualisation, high outliers were omitted: Ireland (225 kg CO_2e per capita in 2019) and Denmark (140 kg CO_2e per capita in 2019) in part A, and Luxembourg (415 kg CO_2e per capita increase between 1995 and 2019) in part B. ICIO=Inter-Country Input–Output tables.

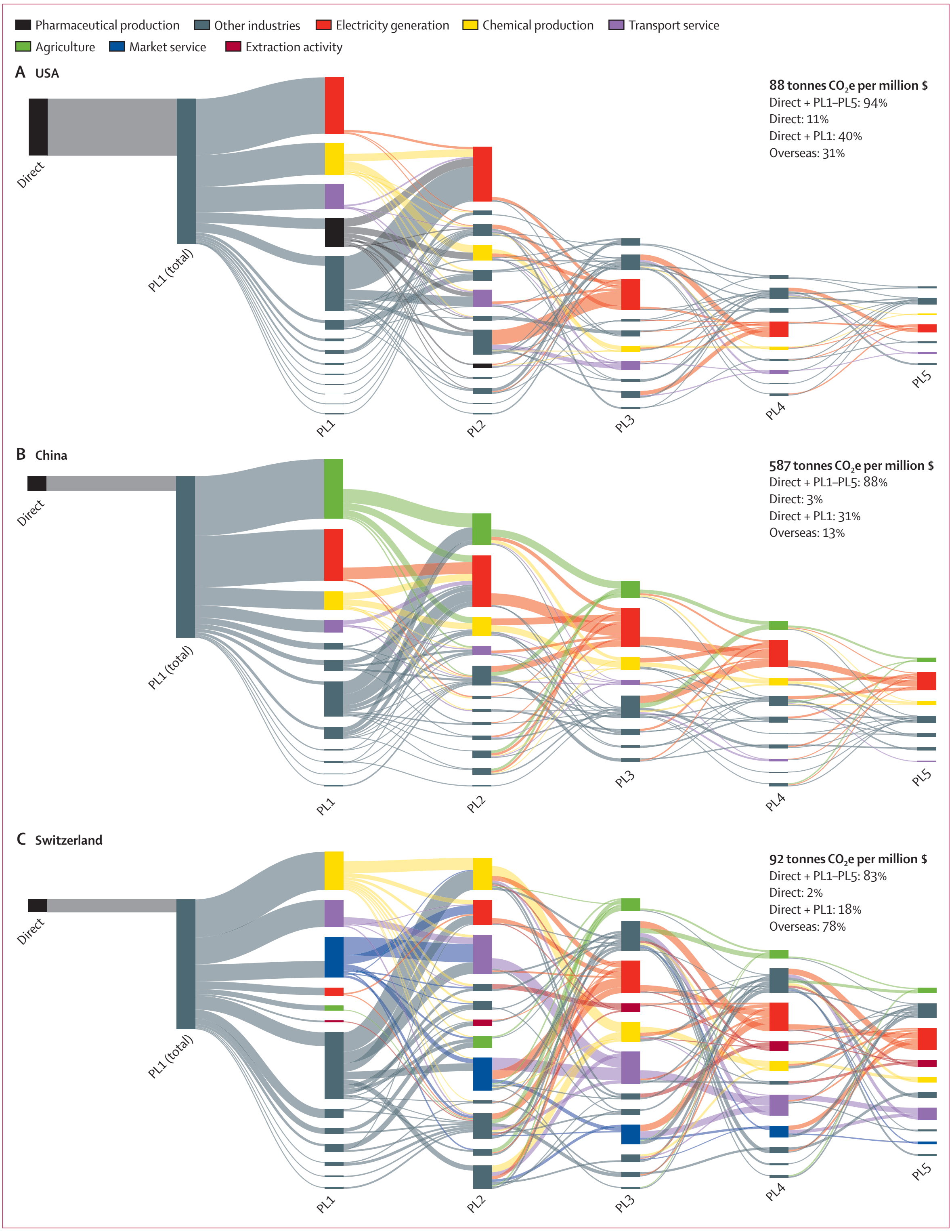

***Figure 3:* Sankey diagrams visualising greenhouse gas emissions across supply chains of top pharmaceutical suppliers**
In each diagram, the vertical bars from left to right highlight key production stages, starting with direct emissions from pharmaceutical production and followed by indirect emissions at production layers upstream (PL1 to PL5). Each flow goes from a downstream production driver (left bar; eg, market service) to its upstream input (right bar; eg, electricity used by the service provider) that generates further emissions. The flow width indicates the relative magnitude of emissions. The three diagrams are not scaled for comparison due to significant differences in emission magnitudes across the supply chains. Currency is US$.

From the production perspective, we examined the supply chains of pharmaceuticals made in the USA, China, and Switzerland, which accounted for half of the global final expenditure on pharmaceuticals in 2019 (note that although these pharmaceuticals were labelled as being made in each of these countries, this term is not used in its literal sense here because supply chains can span globally). Despite all relying on global production networks, the overseas emission displacement differs substantially: 13% for China, 31% for the USA, and 78% for Switzerland. Their total emission intensities also differ substantially, with 88 tonnes CO_2e per million $US for US pharmaceuticals and 92 tonnes CO_2e per million $ for Swiss pharmaceuticals, compared with 587 tonnes CO_2e per million $ for Chinese pharmaceuticals. Downstream production layers account for a small proportion of emissions: direct pharmaceutical production contributes 2% for Switzerland, 3% for China, and 11% for the USA. Including inputs at PL1 increases these proportions to 40% for the USA, 31% for China, and 18% for Switzerland. 17% of the greenhouse gas emissions associated with pharmaceuticals made in Switzerland occur further upstream than the first five production layers.

Sankey diagrams illustrate how emissions accumulate across interconnected supply chains (figure 3). As a result, even though downstream production layers contribute to a small proportion of total emissions, reducing inputs in these layers can have a disproportionate effect on emissions in the upstream layers. For example, in the Swiss supply chain, market services contribute some emissions at PL1 but cause three-times more of those at PL2 due to the service activities' emission-intensive inputs. Additionally, the diagrams highlight utilities, chemical manufacturing, and transportation as the top emitters in all three supply chains: 55% for the USA, 48% for China, and 44% for Switzerland.

To understand the full supply chain emission responsibility and mitigation opportunities of pharmaceutical production within the context of corporate responsibility reporting, we analysed the industry's scope 1–3 emissions by region (figure 4, appendix p 6). Our results show the dominance and growing significance of scope 3 emissions in pharmaceutical production's overall emissions responsibility. By 2019, scope 3 emissions made up at least 50% of total scope 1–3 emissions in 72 of 77 regions, and exceeded 80% in 44 regions.

Of note, emission displacement has risen, with increasing shares of the industry's supply chain emissions occurring overseas (figure 4B). From 1995 to 2019, 51 regions experienced an absolute increase of at least 5% in emissions displaced overseas, and in 26 regions, the increase was 15% or more. For example, for pharmaceuticals labelled as being made in the USA, non-US emissions grew from 15% to 31% (ie, an absolute increase of 16%) between 1995 and 2019. By 2019, for pharmaceutical production in 29 regions, emissions displaced overseas accounted for more than half of the total scope 1–3 emissions.

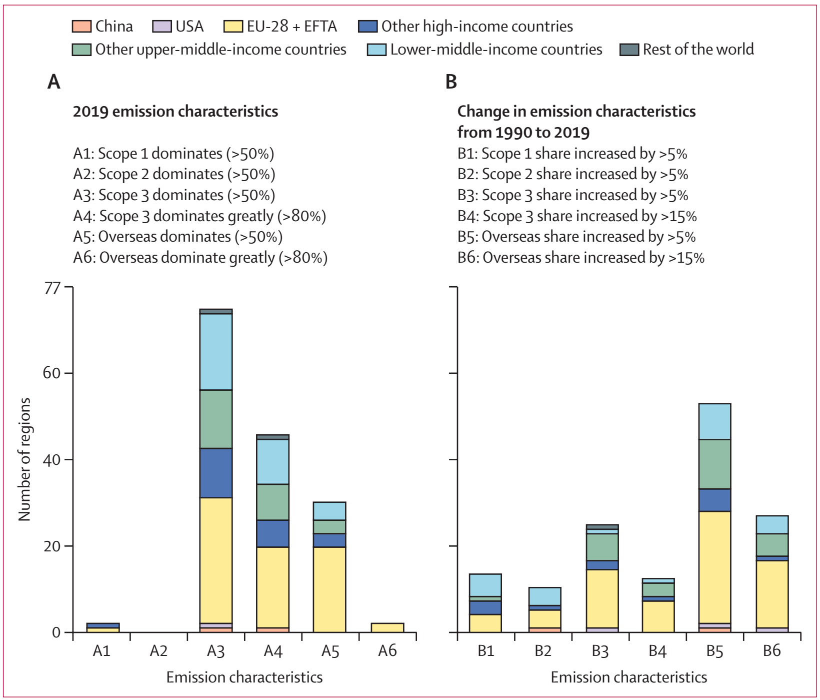

Figure 4: **Scope 1–3 emission analysis showing full supply chain responsibility of pharmaceutical production**
(A) Emission characteristics in 2019. Percentages in A1–A6 represent the share in the sum of scope 1–3 emissions. (B) Changes in emission characteristics from 1995 to 2019. Percentages in B1–B6 show the absolute growth of the share (eg, an increase of >5% means a share grew from 6% to 11% or higher). EFTA=European Free Trade Association.

Previous EE-MRIO studies lacked disaggregated data on pharmaceuticals, often assuming similar emission intensities as chemicals or health-care services.[13,32,33] However, the emission intensity of pharmaceuticals produced in the Netherlands was found to be three-times smaller than that of chemicals.[34] Using the latest EE-MRIO databases from the OECD and Eurostat, we show that pharmaceutical direct emission intensity is 60% higher than that of health-care services, and 80–90% higher for total emission intensity, underscoring the importance of separating pharmaceuticals from other sectors in future assessments (table 2).

The greenhouse gas footprint of pharmaceuticals is growing faster than that of health-care services and the global total, confirming the sector's substantial and increasing climate impact. Moreover, table 2 shows that pharmaceuticals and health-care services together consistently contribute about 3% of the global greenhouse gas footprint. Despite the consistent trends in FIGARO-2024 and ICIO-2023, discrepancies exist between the two databases. Although some variation stems from the databases' different characteristics, these discrepancies underscore the importance of verifying and validating even the most authoritative datasets.

	Latest-year global emission intensity (tonnes CO_2e per million US$, in cyp)				Global contribution (%)		Footprint growth (%)		
	Direct		Total supply chain		Pharmaceuticals	Health-care services	Pharmaceuticals	Health-care services	All
	Pharmaceuticals	Health-care services	Pharmaceuticals	Health-care services					
ICIO-2023									
1995–2019	29·9	18·9	340·7	191·6	1%	2%	77%	53%	49%
2010–19	29·9	18·9	340·7	191·6	1%	2%	15%	2%	10%
FIGARO-2024									
2010–21	15·6	9·7	278·8	149·5	1%	2%	26%	18%	13%
2010–19	17·7	12·0	320·5	182·9	1%	2%	44%	–11%	12%

Our main analysis is based on ICIO-2023 data from 1995 to 2019, excluding the COVID-19 year of 2020. Because FIGARO-2024 covers 2010–21, ICIO-2023 estimates from 2010 to 2019 are more suitable for comparison, given that this period overlaps between databases. cyp=current year prices. ICIO=Inter-Country Input–Output tables.

Table 2: **Validation of global estimates using two recently released databases by international organisations: ICIO-2023 (Organisation for Economic Co-operation and Development) and FIGARO-2024 (Eurostat)**

Discussion

This study presents the first comprehensive assessment of global greenhouse gas emissions related to pharmaceutical consumption and production from 1995 to 2019, using newly compiled global datasets. Our analysis reveals key temporal and spatial patterns that can inform future global trends and region-specific mitigation strategies. We found that the global pharmaceutical greenhouse gas footprint grew by 77%, far outpacing the 49% growth in global greenhouse gas emissions. The main driver was increasing final consumption of pharmaceuticals, especially in China, with technological improvements plateauing since 2008. Although regions such as Europe and China achieved some reductions in emission intensity, they were insufficient to counterbalance the consumption growth. Addressing this challenge will require continued innovation in production efficiency and the adoption of collective action and more targeted strategies.

Our results show a persistent disparity in per-capita pharmaceutical greenhouse gas footprints by income level: in 2019, high-income countries averaged 73 kg CO_2e per capita, compared with 8 kg CO_2e per capita in lower-middle-income countries. The improved resolution of lower-middle-income and upper-middle-income countries in the ICIO-2023 database enabled this insight, emphasising the role of international organisations in developing detailed environmental datasets to uncover such disparities. Our results also revealed a large variation within high-income countries: the USA reached 111 kg CO_2e per capita, whereas several other high-income countries remained at 20–30 kg CO_2e per capita. Given the large variations and the concentration of pharmaceutical production in a few countries, future studies could adopt a more granular regional approach to explore country-specific drivers.

Minimising preventable waste is crucial for mitigating the pharmaceutical greenhouse gas footprint. A previous study suggested that pharmaceutical waste ranges from 3% to 50%,[35] driven by factors such as the expiration of stockpiled pharmaceuticals, overprescription, oversized prescription packages, and limited take-back options.[35–39] Moreover, the global potentially inappropriate use of pharmaceuticals was found to be widespread.[40] Governments have a key role to play by implementing policies that optimise prescription practices, encourage right-sized packaging, facilitate lifestyle counselling, and expand take-back programmes to reduce overuse and unnecessary waste. Innovative business models can also help; in the Netherlands, up to 20% of unused pharmaceuticals were deemed suitable for redistribution,[36] and platforms such as PharmaSwap demonstrate initiatives for redistributing near-expiry drugs.[38] Future research should advance our understanding of pharmaceutical waste management and assess potential solutions in specific local contexts. Lastly, for scalability, government-led efforts on quality control, counterfeiting prevention, and regulatory support are essential.

Our use of EE-MRIO provided novel supply chain insights for producers. It is important to distinguish between the supply chain analysis methods we used: structural path analysis and scope 1–3 accounting. Structural path analysis offers a full, exclusive view of production-related emissions, mapping sectoral hotspots that are often hidden in aggregated estimates. This analysis identified that utilities, chemical manufacturing, and transportation together are the largest emitters in the US (55%), Chinese (48%), and Swiss (44%) supply chains. By contrast, scope 1–3 emissions are shared across production activities, because one industry's direct emissions are another's scope 2 or 3 emissions. This accounting method emphasises shared responsibility and collaborative mitigation. Using the scope 1–3 framework, we delivered a region-specific assessment of pharmaceutical supply chain emissions, showing that, by 2019, scope 3 emissions exceeded 80% in 44 of 77 regions. From 1995 to 2019, 51 regions saw at least a 5% increase in overseas emissions displacement, reflecting a growing globalisation of pharmaceutical production and emission responsibilities, consistent with the increasing share of traded goods and outsourcing over time reported in other studies.[41,42] These findings also suggest transportation as a potential mitigation opportunity.

Based on the two latest EE-MRIO databases from the OECD and Eurostat, our results showed that pharmaceuticals and health-care services together consistently contribute about 3% of the global greenhouse gas footprint, lower than the previously reported 5%.[14] This difference might partly stem from our exclusion of medical appliance purchases, which were included in the previous study. However, another study found that medical appliances account for only a small fraction (5%) of the Dutch health-care sector's carbon footprint,[12] suggesting that this alone might not fully explain the gap. More broadly, variations in environmental footprint estimates across studies often stem from differences in regional and sectoral resolution, as well as database construction methodologies.[43] Our study leverages the latest institutional databases—ICIO-2023 and FIGARO-2024—developed by the OECD and Eurostat, which benefit from direct access to harmonised official statistics, helping to ensure consistency and comparability with national accounts. At the same time, we have carefully refined our modelling approach to maximise methodological rigour and transparency. Over the past decades, academic researchers have led the development of EE-MRIO databases, pioneering data integration techniques despite limited access to official sources. Our work builds upon these efforts while incorporating the advantages of institutional datasets, offering a robust and policy-relevant reassessment of the pharmaceutical and health-care sectors' environmental footprint. The involvement of international organisations in MRIO database development represents a significant step forward, strengthening the foundation for future research and policy applications.

Previous studies on pharmaceuticals' environmental impacts relied mainly on case studies[18] or company data.[19] A previous analysis of 15 top pharmaceutical companies reported an emission intensity of 49 tonnes of CO_2e per million US$ in 2015 (scopes 1 and 2).[19] In comparison, our study estimated the global direct emission intensity (scope 1) at 31 tonnes CO_2e per million $ and the global total emission intensity (scope 1 plus all indirect emissions) at 326 tonnes CO_2e per million $ in 2015. These findings underscore the importance of upstream emissions beyond scope 1 and 2, which are often underrepresented in company reports. Lifecycle assessments have provided detailed assessments of a few specific pharmaceuticals,[18] but they heavily rely on theoretical simulations that omit upstream emissions from services due to data limitations.[18,44] From the consumption perspective, our analysis shows that services contribute over 20% of the pharmaceutical greenhouse gas footprint for Ireland, Belgium, Singapore, Luxembourg, and Switzerland. From a production perspective, services contribute 30% or more of emissions for pharmaceutical supply chains in Ireland, Belgium, Singapore, and Luxembourg. Extending lifecycle assessments of specific medicines with hybrid methods can enable the inclusion of upstream inputs[45] to further identify more sustainable treatment options.

Although we provide a comprehensive global assessment, some limitations remain. Aggregation in EE-MRIO models can obscure variations in product prices and characteristics, leading to estimation errors.[46,47] The ICIO-2023 database reduces this issue by separating pharmaceuticals from chemicals. Further disaggregation of pharmaceuticals is needed to reveal crucial regional differences in consumption and production. Additionally, using monetary data can skew results due to price differences across countries; for example, China's high emission intensity of 587 tonnes CO_2e per million US$ in pharmaceutical expenditure, which we reported in the Results, is likely to reflect lower pharmaceutical prices compared with the USA and Switzerland. Moreover, we adjusted for inflation based on the pharmaceutical industry's inflation, not considering the entire supply chain. However, a broader economic inflation adjustment does not greatly influence the results (appendix p 7). Although beyond the scope of this study, future research should investigate other pertinent environmental impacts of pharmaceuticals, such as resource use, water use, and ecotoxicity, which are particularly relevant to avoid burden shifting when considering mitigation measures.

Furthermore, our estimates probably underestimate the total emissions related to pharmaceuticals. Due to data limitations, we excluded emissions from waste management, emissions embodied in manufacturing equipment, and direct consumer emissions, such as those from inhalers used for respiratory diseases. Additionally, consistent with the conventional consumption-based footprint accounting method, our analysis is limited to pharmaceutical expenditures by final consumers, thus excluding pharmaceuticals purchased by hospitals or for livestock farming. The fractions of indirect versus direct purchases by final consumers can differ by country. A study in China found that hospital pharmaceutical purchases generated twice the emissions of other pharmaceutical purchases.[10] Refining the existing footprint accounting framework would allow future studies to provide a more comprehensive assessment of pharmaceutical-related emissions, complementing the insights provided by this analysis.

In conclusion, the substantial increase in the global pharmaceutical greenhouse gas footprint, coupled with wide cross-country disparities, calls for collective action and more targeted strategies. The pharmaceutical industry must address the stalling emission intensity improvements and enhance supply chain transparency to identify and mitigate emission hotspots. Reducing the dominant indirect emissions on the supply chain requires decarbonising electricity grids, adopting low-carbon fuels in manufacturing processes, and minimising transportation emissions as supply chains grow more complex. Governments play a crucial role in minimising overuse and preventable pharmaceutical waste by implementing and regulating programmes promoting optimised prescription practices, right-sized packaging, lifestyle counselling, and take-back programmes. International collaboration can help mitigate the large variation in per-capita emissions among high-income countries. As pharmaceutical spending rises in lower-income countries, these efforts become even more urgent. Our understanding of waste management, supply chain dynamics, and country-specific emission drivers must be expanded through future research. More detailed micro-level investigations are also essential to identify the specific technological advances and the stagnation observed in our macro-level analysis, enabling more targeted and effective mitigation strategies. Finally, international organisations are essential for improving data granularity, disaggregating pharmaceutical product groups, and enhancing the resolution of low-income countries to enable more accurate and inclusive global assessments.

Contributors

Investigation was carried out by RHH. RHH and RW conceptualised the study. Formal analysis was conducted by RHH and RW. Methodology was developed by RHH, RW, and RH. RW and RH accessed and verified the original data. Supervision was provided by RW, RH, and AT. Validation was conducted by RW. RHH and RW visualised the results. The original draft was written by RHH. RW, RH, AdK, and AT reviewed and edited the original draft. All authors had final responsibility for the decision to submit for publication.

Declaration of interests

We declare no competing interests.

Data sharing

The data sources used in this manuscript, and information on where they can be retrieved, are provided in the appendix (p 7). Only the ICIO-2023 pyp and cyp tables are not publicly available and were collected from the ICIO developers. The code used for the modelling can be made available upon request made to the corresponding author.

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