

Supplementary Information

Chlorinated VSLs Surpass HCFCs in CFC-11-Equivalent Emissions for Ozone Layer Depletion in China

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Supplemental Text

S1 Comparison with other emission estimates of China

Our historical CH₂Cl₂ emissions are generally consistent with those reported in other studies within the respective uncertainty ranges, particularly with the top-down time series emissions reported by An et al.¹ (Figure S1). The differences between our inventory and the estimates of Feng et al.² mainly arise from the CH₂Cl₂ production data used in the two studies. Feng et al.² adopted originally reported production statistics, whereas we employ reconstructed production data that account for inconsistencies in official records (see Text S5 for details). After subtracting feedstock use for HFC-32, the reconstructed production dataset results in a larger amount of CH₂Cl₂ allocated to non-feedstock applications, thereby establishing a more robust upper-bound constraint for emission estimates. Specifically, in our study, the CH₂Cl₂ content in flexible PU foam formulations and EFs for coating utilization and other relevant industries are more representative of current industrial practices. In contrast, Feng et al.² derived lower EFs by referencing voluntary environmental labeling standards that possess low market penetration among commercial products³. Furthermore, their methodology may have interpreted the lack of explicit halogenated hydrocarbon limits in certain standards as an indication of zero emissions. This assumption potentially leads to more conservative estimates of emission intensities compared to the actual industrial practices observed in this study. The bottom-up estimation framework by An et al.¹ assumes that all CH₂Cl₂ consumption—

excluding feedstock utilization for HFC-32 and applications within the pharmaceutical industry—is aggregated into a single, 100% emissive solvent sector. Without a sectoral breakdown, that study potentially overlooks non-emissive pathways, positioning these bottom-up results as an upper-limit constraint on China's total CH₂Cl₂ emissions.

Our CHCl₃ emissions exhibit a gentle increasing trend, whereas the top-down estimates show a rapid rise prior to 2017, followed by a sharp decline thereafter. We derived annually varying CHCl₃ emission factors for China's pulp and paper industry, specifically accounting for the ongoing phase-out of elemental chlorine (EC) bleaching under national environmental mandates. This temporal refinement is consistent with global industrial trends; for instance, recent studies have documented a multi-fold decline in CHCl₃ emission intensities across the United States, Canada, and Japan over the past two decades as advanced bleaching technologies were universally adopted⁴. Owing to the presence of substantial natural sources of CHCl₃, this study quantifies only emissions from natural land surfaces. These emissions are treated as time-invariant, and therefore interannual variability in natural CHCl₃ emissions is not represented in our analysis. This simplified treatment may contribute to the discrepancies between the bottom-up inventory and top-down estimates, particularly in years when natural emissions are expected to vary in response to meteorological or biogeochemical conditions⁵.

S2 Scenario Setting and Policy Rationale

To evaluate future emission trajectories of CH₂Cl₂ and CHCl₃, two scenarios are defined: the Business-As-Usual (BAU) scenario and the Best Practicable Technology (BPT) scenario (as summarized in Table S4). Given that both substances are included in China's *List of Key Controlled Emerging Pollutants*⁶, accelerated emission mitigation driven by technological and regulatory interventions is anticipated. The BAU scenario projects future emissions based on currently implemented policies with emission factors across all industries remaining at historical levels, whereas the BPT scenario reflects enhanced mitigation informed by stringent international regulatory frameworks—such as the U.S. EPA's *Toxic Substances Control Act* (TSCA)⁷ and the EU's *Best Available Techniques (BAT) reference documents*⁸—as well as emerging policy signals in China.

(1) PU Foam, Coatings, and Adhesives Sectors

China has historically implemented a multifaceted regulatory framework targeting volatile organic compounds (VOCs), prioritizing upstream source substitution through mandatory national standards (e.g., GB 30982⁹, GB 33372^{10,11}). While these policies have catalyzed a transition towards water-borne and low-VOC formulations, the mitigation trajectories and current market penetrations of green alternatives diverge significantly across sub-sectors. The resulting evolution of EFs under historical trends is described in Text S6.

Under the BPT scenario, a full phase-out of the remaining high-emission applications is assumed. Internationally, the U.S. issued the *Final Risk Management Rule for Methylene Chloride*⁷ under TSCA in April 2024 that mandated the phase-out of the vast majority of consumer and industrial uses of CH₂Cl₂, with compliance dates mostly set before 2027.

Furthermore, the U.S. EPA's *Significant New Alternatives Policy* (SNAP) effectively prohibited its use in flexible polyurethane (PU) foam production starting from January 3, 2017¹². In China, the regulatory environment is rapidly tightening. The 2021 draft of China's *List of Key Controlled Emerging Pollutants*¹³ proposed a complete phase-out of CH₂Cl₂ as a blowing agent in flexible PU foam by the end of 2025. While this specific mandatory deadline was not retained in the final version, it provides a clear policy signal. Additionally, newly issued mandatory standards (GB 30981.1–2025¹⁴ and GB 30981.2–2025¹⁵) significantly strengthen environmental and health safety requirements for coating products. The *Action Plan for Continuous Improvement of Air Quality*¹⁶ further promotes strict control of construction projects involving paints, adhesives, and cleaning agents with high VOC content, alongside the adoption of low- or zero-VOC alternatives.

Based on these domestic policy trajectories and international precedents, the BPT scenario assumes that the residual usage of high-CH₂Cl₂ formulations in the PU foaming, coating, and adhesive sectors will be progressively phased out over a five-year period from 2026 to 2030. A linear phase-down trajectory is applied to the remaining share of these high-emission applications, which is reflected in the evolution of industry-wide emission factors, reaching complete phase-out (or near-zero limits) by 2030. While actual market transitions may follow non-linear dynamics, this assumption provides a consistent analytical framework for evaluating aggregate mitigation potential.

(2) By-product and Pulp & Paper Sectors

The elemental chlorine bleaching (ECH) process, historically a major source of CHCl₃ emissions in the pulp and paper sector, was classified as an eliminated technology in the 2019 *Guiding Catalogue for Industrial Structure Adjustment*¹⁷. Under the BPT scenario, facilities in China are assumed to progressively optimize processes to meet the best-practice emission levels consistent with the European Commission's BAT reference⁸ by 2035. To reach these targets, emission factors are projected to decrease exponentially, reaching the BAT reference⁸ levels of approximately 0.2 kg/adt for virgin pulp and 3 g/adt for recovered paper pulp by 2035.

For CH₂Cl₂ and CHCl₃ emissions from other inherently high-pollution by-product sources, mitigation is expected to occur synergistically with broader air pollution control efforts. Under the BPT scenario, a continuous regulatory pressure drives a progressive EF reduction of 10% every five years. This trajectory is aligned with China's macro-level targets, such as those outlined in the *Action Plan for Continuous Improvement of Air Quality*¹⁶ and the *Comprehensive Control Plan for Volatile Organic Compounds in Key Industries*¹⁸, which consistently mandate at least 10% reductions in total VOC emissions over successive five-year policy cycles.

S3 Integrated ozone depletion calculation

Integrated ozone depletion (IOD) measures the time-integrated total column ozone (TCO) difference between separate future ozone projections, each following different halogen emissions scenarios¹⁹. Compared to the 'delay in ozone return' metric, IOD is more appropriate

for short-lived species, as it can reflect their contribution to ozone depletion in the short term, even if there is little change in the ozone layer recovery date. A simple equation to calculate the IOD of any emission of a halogenated gas¹⁹:

$$IOD = KE_{eq} \frac{\tau_{atmos}}{\tau_{strat}} \quad (S1)$$

where $K = 100 \pm 16$ DU years per Tg Cl. E_{eq} is the total halogen emission in Tg Cl. τ_{atmos} and τ_{strat} are atmospheric lifetime and stratospheric lifetime, respectively. Pyle et al.¹⁹ provided the IOD from an annually averaged 300 Gg/yr increase in CH₂Cl₂ emissions between 2007-2017 (a period of 11 years) of about 55 DU years, which means Dobson Units of total column ozone depletion integrated over the 11 years. The IOD of CH₂Cl₂ can be scaled based on its total chlorine emission. We would also expect similar τ_{strat} for CH₂Cl₂ and CHCl₃, from the lifetime calculation ($1/\tau_{atmos} = 1/\tau_{tropo} + 1/\tau_{strat}$), since they exhibit nearly identical values for both τ_{atmos} and τ_{tropo} ²⁰. The ratio of $\tau_{atmos}/\tau_{strat}$, which serves as the basis for calculating IOD, as recommended in Pyle et al.¹⁹, would then be similar for CH₂Cl₂ and CHCl₃. Thus, we believe it is appropriate to use CH₂Cl₂ as a proxy for the calculation of IOD for CHCl₃. Their emission levels in 2010 are set as the baseline for IOD calculation. Specifically, the values used for τ_{tropo} , τ_{strat} , and τ_{atmos} for CH₂Cl₂ are 180 days²¹, 1–2 years²², and 142 days¹⁹, respectively.

However, we noticed that the $\tau_{atmos}/\tau_{strat}$ ratio reported for CH₂Cl₂ (20-39%) by Pyle et al.¹⁹ exceeds that of longer-lived species such as CH₃Cl (3%, as documented in the SPARC report²³). This discrepancy likely reflects the high sensitivity of very short-lived species to model-specific transport schemes and the potential inclusion of product gas injection. However, we are unable to fully account for this source of uncertainty within the simplified IOD framework utilized in our manuscript.

S4 Asia CH₂Cl₂ emission allocation

Global emissions of CH₂Cl₂ were obtained from Claxton et al.²⁴. Given that emissions from Boreal Asia are negligible, this study focuses primarily on contributions from Tropical and Temperate Asia. Specifically, CH₂Cl₂ emissions from Tropical Asia were 341.4 ± 22.7 Gg/yr in 2006 and 454.2 ± 28.7 Gg/yr in 2017, while emissions from Temperate Asia were 89.9 ± 22.8 Gg/yr in 2006 and 590.7 ± 28.4 Gg/yr in 2017. The proportion of Tropical Asian emissions relative to total Asian emissions decreased from 79% in 2006 to 43% in 2017. Based on this trend, a linear decline in the relative contribution of Tropical Asia is assumed in our analysis.

S5 Reconstruction of CH₂Cl₂ and CHCl₃ production data

We recalculate the value of CH₂Cl₂ production and CHCl₃ production²⁵ based on downstream application data, as the reported values of individual CH₂Cl₂ and CHCl₃ production are not sufficiently reliable. Considering that CHCl₃ is primarily used in HCFC-22 production and, to a lesser extent, in the pharmaceutical industry, we estimate CHCl₃ consumption based on its major downstream applications as well as CHCl₃ import and export. HCFC-22 production has been historically regulated under the Montreal Protocol and is subject to mandatory annual

reporting, rendering the corresponding production data relatively reliable. Therefore, CHCl_3 consumption for feedstock use can be inferred from reported HCFC-22 production (from the Chinese Hydrochlorofluorocarbons Production Phase-out Management Plan by the Ministry of Ecology and Environment and ChinaIOL²⁶). By additionally accounting for pharmaceutical uses, which represent approximately 8–10% of total CHCl_3 consumption⁵, the total CHCl_3 production can be estimated. Given the combined production of CH_2Cl_2 and CHCl_3 , the remaining fraction after subtracting CHCl_3 is attributed to CH_2Cl_2 production. This method anchors calculations to well-documented downstream applications, improving the reliability and consistency of production estimates.

S6 Historical emission factor derivation

As detailed in the Main Text (Methods), a default baseline uncertainty of $\pm 10\%$ is systematically applied to all single-value emission factor cataloged in Supplementary Tables S1–S3, while the rationale for specific exceptions (such as the 40% uncertainty for the flexible PU foam sector) is elaborated below.

(1) Flexible PU Foaming sector

CH_2Cl_2 functions exclusively as a physical blowing agent (PBA) in the flexible polyurethane (PU) foam industry, facilitating cellular expansion through phase transition without participating in chemical synthesis. Consequently, the total mass of CH_2Cl_2 incorporated into the formulation is theoretically committed to eventual atmospheric release. Consequently, the entire quantity of CH_2Cl_2 added to the formulation is theoretically destined for eventual emission in the absence of capture measures²⁷. Following *Handbook of Polyurethane Products Manufacturing*²⁸, the baseline EF was parameterized at 0.11 g CH_2Cl_2 /g of flexible foam produced.

While end-of-pipe control technologies, such as activated carbon adsorption, may be deployed, their effective mitigation potential is fundamentally constrained by operational requirements. However, it is important to note that foaming workshops necessitate exceptionally high ventilation rates to dilute highly toxic toluene diisocyanate (TDI) vapors. This high-volume dilution results in extremely low CH_2Cl_2 concentrations in the effluent gas, which significantly constrains the capture efficiency of adsorption systems. Previous research suggests that even when exhaust systems are optimized for vapor recovery, the net capture efficiency of CH_2Cl_2 typically ranges between 33% and 46%²⁹. This indicates that for facilities equipped with abatement technologies, actual emissions are approximately 30% to 50% lower than the theoretical values derived from the formulation. Industrial formulations exhibit substantial heterogeneity driven by target foam specifications, such as density and hardness. Notably, CH_2Cl_2 loading rates frequently exceed baseline values in the production of specialized low-density foams. Consequently, the 40% uncertainty parameter is employed as a robust bounding estimate. This interval simultaneously accounts for the potential attenuation of emissions through abatement systems and the inherent variability of raw material consumption across diverse and non-uniform production lines.

(2) Adhesive and coating industries

To achieve volatile organic compound (VOC) mitigation, the Chinese government has deployed a multifaceted regulatory framework targeting the adhesive and coating industries. Key interventions include the enforcement of mandatory national standards regarding VOC content limits and the introduction of a consumption tax on coatings in 2015^{18,30}. These mandates prioritize upstream source substitution, specifically incentivizing the transition toward water-borne formulations.

The content of halogenated hydrocarbons (CH_2Cl_2 , 1,2-dichloroethane, 1,1,1-trichloroethane, and 1,1,2-trichloroethane) in adhesive products must comply with the regulations set in GB 30982⁹ or GB 33372^{10,11}. Although relevant standards have not tightened the concentration limits for halogenated hydrocarbons (primarily CH_2Cl_2) in adhesives, the market penetration of these high-emission formulations has undergone a sustained decline. This shift has led to a decrease in the overall EF for the adhesive industry, which dropped from approximately 3.8 g/kg in 2010 to 2.8 g/kg in 2022. The calculation methodology is based on the consumption volumes of different adhesive types^{31–34} and their respective halogenated hydrocarbon limits, including GB 18583-2008³⁵, GB 30982-2014⁹, and GB 19340-2014³⁶. Under these standards, for solvent-based adhesives, the concentration of halogenated hydrocarbons is restricted to 5 g/kg for neoprene-based types and 50 g/kg for all other varieties, while CH_2Cl_2 levels in SBS (Styrene-Butadiene-Styrene block copolymer) adhesives must not exceed 50 g/kg.

Within the coating sector, mitigation trajectories diverge between sub-sectors. In architectural coatings, where water-borne technologies had already achieved mainstream status by 2010, the potential for further CH_2Cl_2 attenuation is marginal. Conversely, industrial coatings maintain a lower adoption rate of low-VOC alternatives—accounting for less than 20% of the market as of 2019, according to the Ministry of Ecology and Environment¹⁸. Consequently, the aggregate CH_2Cl_2 EF for the coating industry has not exhibited a statistically significant downward trend. To capture the longitudinal impact of these disparate regulatory outcomes, this study adopts annually varying EFs. These factors were derived by integrating the consumption volumes of specific coating categories with their respective water-borne market shares, synthesized from the framework established by Qi et al.³⁷ and applicable mandatory national standards, including GB 18581-2009³⁸, GB 30981-2014³⁹, GB 38469-2019⁴⁰, GB 18581-2020⁴¹, GB 18582-2020⁴², GB 24409-2020⁴³, GB 30981-2020⁴⁴. Specifically, under these standards, the halogenated hydrocarbon content in solvent-based coatings is capped at 1% for industrial and marine coatings, and 0.1% for vehicle, architectural, and wood (furniture) coatings.

(3) Pharmaceutical industry

The EF of CH_2Cl_2 from the pharmaceutical industry was calculated based on the material balance using Eq.(S2)²:

$$EF_{pha} = b \times (1 - K) \times 10^3 \times [i \times (1 - \alpha) + (1 - i)] \quad (\text{S2})$$

Here, EF_{pha} is the CH_2Cl_2 emission required to produce a ton of penicillin or cephalosporin, kg/t; b represents the ratio of the solvent mass to the penicillin product or the cephalosporin

mass needed for production (7-8); K is the solvent recovery (85%-97%); α is the proportion of waste gas treated in the pharmaceutical industry as a whole 88%-95%; i is the proportion of waste gas treated at an individual plant. The proportion of waste gas undergoing treatment at the individual plant was parameterized at 50% before 2017². Following the implementation of the National Mandatory *Emission Standard of Air Pollutants for the Pharmaceutical Industry* (GB 37823-2019)⁴⁵ in late 2017, this ratio was linearly scaled to reach 100% by 2020. The mean value of EF_{pha} is 0.37 g/g when the proportion of waste gas treated at an individual plant is 50%.

(4) Pulp and paper-making industry

We validated our AOX (Adsorbable Organic Halogens) EFs for the pulp and paper industry using the *Guidelines for Advanced Applicable Technologies for Energy Saving and Emission Reduction in Light Industry*⁴⁶ from the Ministry of Industry and Information Technology of China (MIIT). These guidelines provide specific AOX emission ranges for the two dominant pulping processes in China: wheat straw chemical pulping (representing the majority of domestic virgin pulp) and deinked recovered paper pulping. To ensure consistency across varying production environments, all values are reported in Air-Dry Tonnes (adt), a standard industry measure representing pulp mass at a theoretical 10% moisture content.

To derive a representative national average, we performed a weighted analysis based on the technological distribution and raw material structure of the Chinese industry. According to the MIIT (2012) framework, ‘Advanced Levels’—representing the top-performing facilities—account for approximately 20% of virgin pulp production and 70% of recovered paper pulp production. For virgin pulp, emission intensities range from 0.25–0.72 kg/adt at the advanced level to 1.0–1.2 kg/adt at the general level. For recovered paper pulp, these values are significantly lower, ranging from 0.01–0.15 kg/adt (advanced) to 0.15–0.3 kg/adt (general). By integrating these technological splits with the industry’s raw material structure—where recovered paper pulp consistently accounted for 70–80% of total production⁴⁷—we determined that the composite AOX emission intensity for the Chinese industry ranges from 0.252 to 0.422 kg/adt for the early 2010s.

Based on the fundamental chemical coupling between liquid-phase AOX and gas-phase CHCl_3 , which are co-generated through identical chlorination and haloform pathways, we adopted the calculated AOX emission range as a scientifically justified proxy for the potential CHCl_3 emission levels. While CHCl_3 is more volatile, the AOX intensity serves as a reliable indicator of the total chlorination capacity of a given facility. This alignment is supported by the fact that the calculated AOX range (0.252–0.422 kg/adt) is fully encapsulated within the CHCl_3 EF (0.053–0.454 kg/adt) from previous literature^{48–50}. This overlap demonstrates that our chosen parameters accurately capture the technological profile of the Chinese paper industry during the study period.

Regarding temporal dynamics, our assumption that the industry-wide average EF converged to the 2012 ‘Advanced Level’ by 2023 is anchored in the sector’s pioneering role in China’s environmental reforms. Specifically, the share of advanced production processes (as

categorized in 2012) for virgin and recovered paper pulp increased linearly from 20% and 70% in 2012, respectively, to 100% by 2023. As mandated by the State Council, the pulp and paper industry was among the first to implement the Pollutant Discharge Permitting System, requiring mills to meet technology-based standards as early as 2017⁵¹. Furthermore, the *Guiding Catalog for Industrial Structure Adjustment* (2019 Edition)¹⁷ officially designated Elemental Chlorine Bleaching (ECH) as an ‘Eliminated Category’, providing a statutory mandate for the decommissioning of chlorine-intensive legacy assets. Combined with the stringent decarbonization and ‘Green Manufacturing’ objectives of the 14th Five-Year Plan (2021–2025)⁵², the 2012 advanced benchmarks have effectively transitioned from elective performance targets into the minimum requisite standards for legal operation and market viability by 2023. Consequently, utilizing these parameters provides a robust and conservative framework that reflects the technological modernization of the industry and the substantial environmental dividends accrued from the universal adoption of Elemental Chlorine-Free (ECF) processes. The final calculated EFs are shown in Supplementary Table S3.

(5) Water treatment

For the drinking water treatment sector, the concentration of CHCl_3 in finished tap water typically does not exceed a regulatory or observed upper limit of 100 $\mu\text{g/L}$, with empirical mean values oscillating between 10 and 20 $\mu\text{g/L}$ ^{53,54}. Under a conservative assumption of a 100% volatilization-to-emission efficiency, the atmospheric EF for this sector was parameterized at a range of 1×10^{-2} to 2×10^{-2} g/m^3 water treated.

For the wastewater treatment sector, the total EF (EF_{Total}) for CHCl_3 was quantified by integrating primary influent volatilization (EF_{pri}) and secondary gaseous release during effluent chlorination (EF_{sec}), as defined in Eqs. (S3)–(S5).

$$EF_{Total} = EF_{pri} + EF_{sec} \quad (\text{S3})$$

$$E_{pri} = C_{inf} \times f_{aeration} \times 10^{-6} \quad (\text{S4})$$

$$E_{sec} = C_{eff,i} \times f_{escape} \times 10^{-6} \quad (\text{S5})$$

The aqueous concentrations of CHCl_3 in the influent ($C_{inf,i}$) and effluent ($C_{eff,i}$) were parameterized at 7.0 $\mu\text{g/L}$ and 14.6 $\mu\text{g/L}$, respectively, based on localized measurements in Chinese wastewater treatment plants (Li et al.⁵⁵). To account for phase partitioning during biological treatment, an aeration stripping fraction ($f_{aeration}$) of 0.18 was adopted (Zhu et al.⁵⁶). Furthermore, given the high vapor pressure and biological recalcitrance of CHCl_3 in oxygenated surface waters, an ultimate environmental escape fraction (f_{escape}) of 1.0 was applied⁵⁷, assuming complete volatilization within the receiving water boundary based on low concentration in natural water. Based on these parameters, the integrated EF for the wastewater treatment sector was calculated to be 1.6×10^{-2} g/m^3 .

(6) Waste incineration

To ensure the reliability of our emission inventory, we utilized localized empirical data from a comprehensive field study of four municipal solid waste incineration plants in North China⁵⁸.

To mitigate the impact of facility-specific outliers driven by heterogeneous waste streams, we adopted the mean mass fractions of specific halocarbons within the total VOC (TVOC) profile as representative parameters for the sector. Specifically, CH₂Cl₂ and CHCl₃ accounted for an average of 4.58% and 0.73% of the TVOC emissions, respectively. By applying these mean fractions to the observed TVOC emission baseline (2.43 ± 2.27 g/tonne-waste), we derived consolidated EFs of 0.111 ± 0.104 g/tonne-waste for CH₂Cl₂ and 0.018 ± 0.017 g/tonne-waste for CHCl₃.

(7) CH₂Cl₂ and CHCl₃ production sector

For the CH₂Cl₂ and CHCl₃ production sector, this study adopted EFs ranging from 0.5% to 4% according to the IPCC guidelines^{59,60}. Recent inverse modeling and plant-level studies in China by Li et al.⁶¹ reported aggregate EFs of $4\% \pm 2\%$ for CH₂Cl₂ and $2\% \pm 0.6\%$ for CHCl₃. This facility has a production capacity of approximately 400 Gg yr⁻¹, accounting for ~13% of the national production capacity in 2019, supporting its representativeness for the Chinese chloromethane production sector. However, it is critical to note that these observations were conducted at integrated industrial parks where chloromethane production is co-located with downstream facilities, such as HFC-32 and HCFC-22 production lines. Consequently, these observational values represent the cumulative emission intensity of the entire industrial chain—including synthesis, feedstock transfer, and utilization. By maintaining separate IPCC process EFs, our bottom-up model can partition these emissions into their respective sectors while ensuring the total remains consistent with these system-wide observational constraints.

S7 Activity data projection

Using activity level data for each sector (Y) and relevant historical socio-economic parameters (X), linear regression models ($Y = \alpha \cdot X + \beta$) were developed to forecast future activity data of the future CH₂Cl₂/CHCl₃ emission sector in the BAU and BPT scenarios. The least-square method is used to solve the parameter α and β . The selected parameters and regression results are shown in the Table S5&S6. Future gross domestic product (GDP) is based on China's overall development goals by 2035 that per capita GDP will attain the level of moderately developed countries. The required average annual growth rate of China's per capita GDP from 2023 to 2035 is 4.61%⁶². The population projection is derived from mean estimates of China from *World Population Prospects 2024*⁶³. Future coal combustion estimate is from *China Energy Outlook 2060 (2025 Edition)*⁶⁴. Production of penicillin and cephalosporin compounds is set as the mean value of 2010-2023, as China has listed antibiotics in the *List of Key Controlled Emerging Pollutants*⁶ and strengthened antimicrobial stewardship⁶⁵.

The amount of CH₂Cl₂ used for HFC-32 production was derived from the annual HFC-32 production and the mass balance of CH₂Cl₂-to-HFC-32 conversion, with a conversion efficiency of 95% (following consultation with industry experts). Future production of HFC-32 is set at a constant value as the production quota in 2025, as HFC-32 has a lower global warming potential (GWP) among HFCs and will not be phased down with priority.

341 The amount of CHCl_3 used for HCFC-22 production was derived from the annual HCFC-22
342 production and the mass balance of CHCl_3 -to-HCFC-22 conversion, with a conversion
343 efficiency of 96.5% (following consultation with industry experts). Future production of
344 HCFC-22 is divided into two components: feedstock use and ODS use. HCFC-22 is utilized as
345 a feedstock for manufacturing TFE (tetrafluoroethylene) and HFP (hexafluoropropene). The
346 increase in TFE/HFP output²⁶ has driven the growth in the production of HCFC-22 and CHCl_3 .
347 Notably, HCFC-22 production for feedstock use has surged by about 70% between 2018 and
348 2023, marking a significant acceleration compared to previous trends. In this study, the average
349 annual growth rate of 9.2% adopted for HCFC-22 production as feedstock is derived from data
350 spanning the period from 2010 to 2024. HCFC-22 production for ODS use would be gradually
351 phased down in accordance with the Montreal Protocol, but this effect is insignificant compared
352 with the rapid growth of feedstock use for TFE/HFP production.

Supplemental Tables

Table S1. Method for CH₂Cl₂ emission calculation

Sector	Activity data	Historical emission factor*	Emission allocation parameter
Production leakage	CH ₂ Cl ₂ production ²⁵	0.5 – 4% ^{59,60}	Production capacity of chloromethane plants ²⁵
Feedstock use leakage	HFC-32 production ⁶⁶	0.5% ⁶⁰	Production quota of each HFC-32 plant ^a
Pharmaceutical industry	Production of penicillin and cephalosporin compounds ⁶⁷	0.37 g/g ²	provincial production of penicillin and cephalosporin compound ⁶⁷
Industrial cleaning	Sectorial CH ₂ Cl ₂ consumption (8% of total CH ₂ Cl ₂ consumption) ⁶⁸	100% ²	Industrial added value ⁶⁹
Adhesive utilization	Adhesive consumption ⁷⁰	Time-dependent, see Table S3	Completed construction area ⁷¹
Coating utilization	Coating consumption ³³	Time-dependent, see Table S3	Industrial added value ⁶⁹
PU foaming	Output of flexible PU foam ⁷²	CH ₂ Cl ₂ content in flexible PU foam formulation (0.11 with 40% uncertainty) ²⁸	Provincial population ⁶⁹
Biomass burning	National emission of CO and CO ₂ from biomass burning ⁷³	2.48×10^{-5} for CO and 3.45×10^{-6} for CO ₂ ⁷⁴	Provincial emission of CO and CO ₂ from biomass burning ⁷³
Coal production	Coal production ⁷⁵	1×10^{-9} g/t ²	Provincial coal production ⁷⁵
Coal combustion	Coal consumption ⁷⁵	$6.38 \times 10^{-2} \pm 9.88 \times 10^{-3}$ g/t ⁷⁶	Provincial coal consumption ⁷⁵
Waste incineration	Waste incineration volume ⁷⁷	$1.11 \times 10^{-1} \pm 1.04 \times 10^{-1}$ g/t ⁵⁸	Waste incineration volume ⁷⁷
Waste landfill	Waste landfill volume ⁷⁷	5 g/t ⁷⁸	Waste landfill volume ⁷⁷
Sintering	Sintering production ⁷⁹	5.74×10^{-2} g/t ⁸⁰	Provincial sintering production ⁷⁹
Pig iron	Pig iron production ⁷⁹	5.92×10^{-2} g/t ⁸⁰	Provincial pig iron production ⁷⁹
Crude steel	Crude steel production ⁷⁹	1.7×10^{-1} g/t ⁸⁰	Provincial crude steel production ⁷⁹

Notes: ^a Ecology and Environment Ministry of China; *If multiple values from different references were given, a uniform distribution between the values would be adopted to calculate the emissions and uncertainties. For emission factors reported as single values, a default uncertainty of 10% was assumed unless otherwise specified.

Table S2. Method for CHCl₃ emission calculation

Sector	Activity data	Historical emission factor*	Emission allocation parameter
Production leakage	CHCl ₃ production ²⁵	0.5 – 4% ^{59,60}	Production capacity of chloromethanes plants ²⁵
Feedstock use leakage	HCFC-22 production ^{a, 26}	0.5% ⁶⁰	Historical production of each HCFC-22 plant ^a
Pharmaceutical industry	Consumption of CHCl ₃ in the pharmaceutical industry (8-10% of total CHCl ₃ consumption) ²⁵	5-16% ⁵	Output of chemical active pharmaceutical ingredients ⁶⁷
Pulp and paper industry	Pulp production ⁴⁷	Time-dependent, see Table S3	Machine-made paper and paperboard ⁷¹
Drinking water treatment	Drinking water treatment volume ⁷⁷	1×10^{-2} to 2×10^{-2} g/m ³ ^{53,54}	Drinking water treatment volume ⁷⁷
Wastewater treatment	Wastewater treatment volume	1.59×10^{-2} g/m ³ ⁵⁵⁻⁵⁷	Wastewater treatment volume ⁷⁷
Other water treatment	70% of emissions from drinking water treatment and wastewater treatment ⁴⁸	-	-
Biomass burning	National emission of CO and CO ₂ ⁷³	6.9×10^{-7} for CO 7.7×10^{-8} for CO ₂ ⁷⁴	Provincial emission of CO and CO ₂ ⁷³
Coal combustion	Coal consumption ⁷⁵	$2.9 \times 10^{-3} \pm 1.1 \times 10^{-4}$ in g/t ⁷⁶	Coal consumption ⁷⁵
Waste incineration	Waste incineration volume ⁷⁷	$1.8 \times 10^{-2} \pm 1.7 \times 10^{-2}$ g/t ⁵⁸	Waste incineration volume ⁷⁷
Waste landfill	Waste landfill volume ⁷⁷	6.33×10^{-1} g/t-waste ⁷⁸	Waste landfill volume ⁷⁷
Livestock	CH ₄ emission from livestock ⁸¹	2×10^{-5} g/g CH ₄ ^{48,82}	CH ₄ emission from livestock ⁸¹
Natural soil	National area ⁸³	$4 - 13 \mu\text{g m}^{-2} \text{ day}^{-1}$ ⁸⁴	Provincial area ⁸³

Note: ^a Chinese hydrochlorofluorocarbons production phase-out management plan (HPPMP); *If multiple values from different references were given, a uniform distribution between the values would be adopted to calculate the emissions and uncertainties. For emission factors reported as single values, a default uncertainty of 10% was assumed unless otherwise specified.

Table S3. Time-variant historical emission factor

Years	Adhesives utilization * (g/kg)	Coating utilization (g/kg)	Pulp and paper-making Sector (kg/adt)
2010	3.84	3.14	0.272-0.445
2011	3.67	3.22	0.265-0.437
2012	3.58	3.22	0.243-0.412
2013	3.50	3.03	0.215-0.387
2014	3.41	3.71	0.195-0.371
2015	3.32	3.64	0.174-0.351
2016	3.24	3.45	0.157-0.337
2017	3.15	3.55	0.146-0.331
2018	3.06	3.38	0.150-0.347
2019	2.97	3.57	0.139-0.345
2020	2.89	3.36	0.129-0.343
2021	2.80	3.45	0.116-0.341
2022	2.79	3.16	0.104-0.341
2023	2.79	3.11	0.089-0.337

* The emission factors for adhesive utilization for the intervening years (2012–2020) were estimated through linear interpolation based on the data points of 2011 and 2021 to ensure a continuous time series.

Table S4. Scenario design summary

Scenario name	Scenario design
Business-As-Usual Scenario	• The production of paint removers containing CH₂Cl₂ or CHCl₃ is prohibited. • In accordance with the Technical Standards for Cosmetic Safety, CH₂Cl₂ is prohibited from being used as a cosmetic ingredient. • In accordance with the Limits for Volatile Organic Compounds Content in Cleaning Agents (GB 38508), the total content of CH₂Cl₂, CHCl₃, trichloroethylene, and tetrachloroethylene in water-based cleaning agents, semi-water-based cleaning agents, and organic solvent-based cleaning agents shall not exceed 0.5%, 2%, and 20%, respectively. • In accordance with the CH₂Cl₂ emission control requirements specified in standards such as the Emission Standards for Pollutants from Petroleum Chemical Industry (GB 31571), Emission Standards for Pollutants from Synthetic Resin Industry (GB 31572), and Emission Standards for Water Pollutants from Chemical Synthetic Pharmaceutical Industry (GB 21904), compliance with emission standards shall be implemented. • In accordance with the CHCl₃ emission control requirements specified in standards such as the Emission Standards for Pollutants from Petroleum Chemical Industry (GB 31571), compliance with emission standards shall be implemented. • Emission factors across all industries remain at historical levels.
Best Practicable Technology scenario	Emissive Applications (PU Foam, Adhesives, and Coatings): • Phase-out Timeline: A decisive five-year window (2026–2030) for the complete removal of CH₂Cl₂ and CHCl₃ in these sectors. Use in PU flexible foam production is prohibited (starting from 2026, complete phase-out by 2030). • Modeling Logic: The residual aggregate emission factors (representing the remaining high-emission applications relative to the 2025 baseline) are assumed to decline linearly by 20% annually, reaching complete phase-out by 2030. Pulp and Paper Industry: • Technological Transition: Accelerated elimination of ECH, which was classified as an eliminated technology in China's 2019 Industrial Structure Adjustment catalogue. • Mitigation Target: Emission factors decrease exponentially to achieve the European Commission BAT reference levels (~0.2 kg/adf for virgin pulp and 3 g/adf for recovered paper pulp) by 2035. Other Industrial By-product Sources Reduction Strategy: • Mitigation occurs synergistically with broader national air pollution control efforts targeting volatile organic compounds (VOCs). • Reduction Rate: Assumes a progressive 10% reduction in emission factors every five years. This trajectory is strictly aligned with China's macro-environmental targets, such as those in the Action Plan for Continuous Improvement of Air Quality, which mandate >10% total VOC reductions per five-year cycle.

Table S5. Method for activity data projection for CH₂Cl₂ emission calculation

Sector	Activity data	Activity data projection	α	β	R²
Production leakage	CH ₂ Cl ₂ production	Depends on consumption	-	-	-
Feedstock use leakage	HFC-32 production	Constant value as HFC-32 production quota in 2025	-	-	-
Pharmaceutical industry	Production of penicillin and cephalosporin compounds	Historical mean (2010-2023)	-	-	-
Industrial cleaning	Sectorial CH ₂ Cl ₂ consumption	GDP	7.7×10^{-5}	1.22	0.66
Adhesive utilization	Adhesive consumption	4.2% (sectorial 14th Five-Year Plan) ⁸⁵	-	-	-
Coating	Coating consumption	4% (sectorial 14th Five-Year Plan) ⁸⁶	-	-	-
PU foaming	Output of flexible foam	GDP	1.9×10^{-3}	610	0.84
Biomass burning	National emission of CO ₂ and CO	Historical mean (2010-2023)	-	-	-
Coal production	Coal production	91% of consumption (based on 2023)	-	-	-
Coal combustion	Coal consumption	China Energy Outlook 2060 (2025 Edition) ⁶⁴	-	-	-
Sintering	Sintering production	Same with pig iron production	-	-	-
Pig iron	Pig iron production	GDP	3.3×10^{-4}	480	0.91
Crude steel	Crude steel production	GDP	4.8×10^{-4}	480	0.91

Table S6. Method for activity data projection for CHCl₃ emission calculation

Sector	Activity data	Activity data projection	α	β	R ²
Production leakage	CHCl ₃ production	Depends on future consumption	-	-	-
Feedstock use leakage	HCFC-22 production	National program for ODS use and 9.2% for feedstock use based on historical trend	-	-	-
Pharmaceutical industry	Consumption of CHCl ₃ in the pharmaceutical industry	GDP	5.9×10^{-5}	5.9	0.77
Pulp and paper industry	Pulp production	Based on the sectorial plan ⁸⁷	-	-	-
Drinking water treatment	Drinking water treatment volume	GDP	3.0	6.2×10^6	0.89
Wastewater treatment	Wastewater treatment volume	GDP	4.7	1.7×10^6	0.99
Other water treatment	70% of emissions from drinking water treatment and wastewater treatment	-	-	-	-
Biomass burning	National emission of CO ₂ and CO	Historical mean (2010-2023)	-	-	-
Coal combustion	Coal consumption	Historical mean (2010-2023)	-	-	-
Waste management	Volume of harmless waste treatment (waste incineration volume + waste landfill volume)	Mean value of projected population	23	-2.9×10^{-6}	0.99
Waste incineration	Waste incineration volume	Volume of harmless waste treatment minus incineration volume	-	-	-
Waste landfill	Waste landfill volume	Decrease to zero by 2025	-	-	-
Livestock	CH ₄ emission from livestock	Historical mean (2010-2020)	-	-	-
Natural soil	National area	-	-	-	-

Supplemental Figures

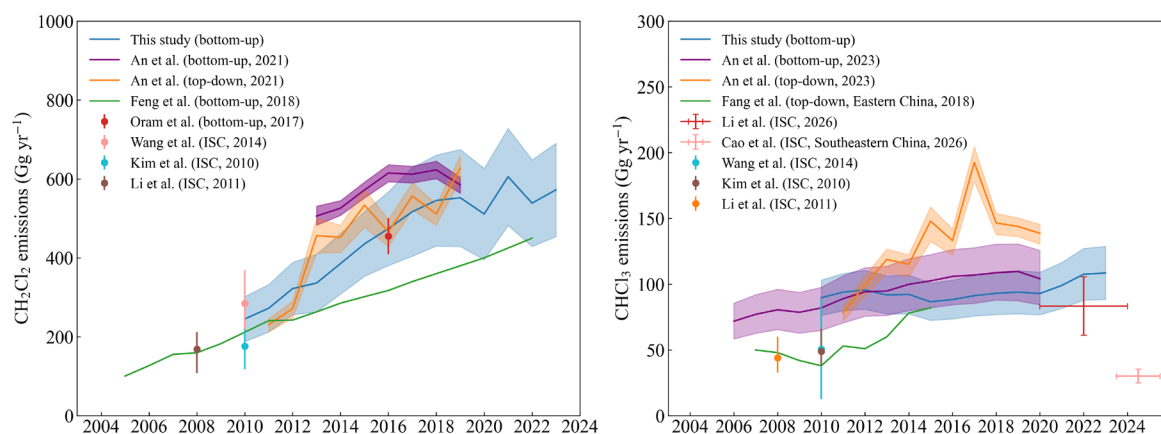


Figure S1. CH_2Cl_2 and CHCl_3 emissions of China. Results from other studies^{1,2,5,88–93} are also shown. ISC means ‘interspecies correlation’ method.

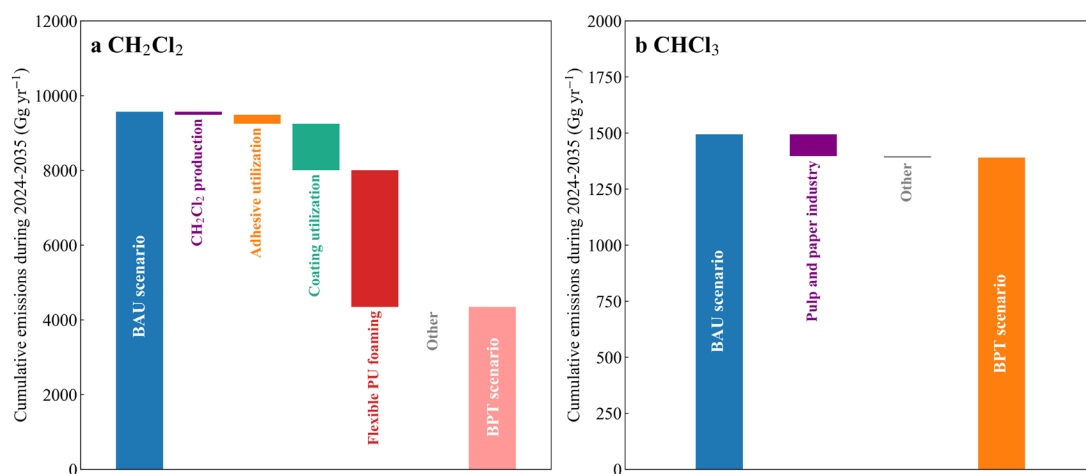


Figure S2. Cumulative emission of CHCl₃ and CH₂Cl₂ during 2024-2035 and emission reduction potential in all sectors. The first and last bars in each panel represent the cumulative emissions during 2024-2035 in the BAU scenario and the BPT scenario, respectively. Other bars in each panel represent the cumulative emission reduction potential from each sector.



Figure S3. Administrative Map of the People's Republic of China. The map is sourced from the Ministry of Natural Resources of China.

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