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Environmental Implications of Ozone-Depleting Substances: A Critical Assessment of Global and National Mitigation Strategies

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Abstract

Stratospheric ozone depletion remains a critical environmental and public health concern, driven by emissions of ozone-depleting substances (ODS) from industrial, agricultural, and domestic sources. Despite the near-universal global commitment demonstrated by the ratification of the Montreal Protocol by nearly 200 countries, operational implementation gaps hinder the complete recovery of the ozone layer. This research examines the environmental consequences of ozone-depleting substances (ODS) and evaluates the efficacy of both global and national mitigation strategies. The objectives include examining global progress in ODS reduction, evaluating national implementation performance, analysing existing policy instruments, identifying persistent challenges, and exploring associated co-benefits and trade-offs. This study employs a qualitative research design informed by the Multi-Level Perspective (MLP) theory of socio-technical transitions, utilising secondary data sourced from peer-reviewed literature, international environmental reports, and reputable datasets such as OWID. A systematic review and thematic content analysis were utilised to synthesise insights in accordance with the research objectives. Research indicates that global ODS emissions have decreased by more than 99% since 1989 due to the Montreal Protocol's regulatory framework, with observable trends of ozone recovery in recent decades. National-level implementation is inconsistent, especially in developing economies, where challenges include informal service networks, limited technician capacity, weak enforcement mechanisms, and slow adoption of low global warming potential (GWP) substitutes. Legacy refrigerant banks pose risks, and the climate trade-offs linked to high-GWP alternatives remain significant. The study concludes that the effectiveness of the global governance architecture depends on strengthening national enforcement systems, expediting low-GWP transitions, expanding reclamation infrastructure, and incorporating ozone-climate-health policies to ensure equitable environmental benefits.

Keywords: Ozone depletion, ozone-depleting substances, Montreal Protocol, low-GWP alternatives, refrigerant banks, enforcement capacity.

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1. Introduction

The stratospheric ozone layer is a narrow yet crucial shield that absorbs the Sun’s harmful ultraviolet (UV-B) radiation, thereby protecting terrestrial and aquatic ecosystems, human health, and agricultural productivity (Egorova et al., 2023; WMO & UNEP, 2022). Since the late twentieth century, anthropogenic halogenated compounds, chiefly chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl bromide, and hydrochlorofluorocarbons (HCFCs), have catalyzed catalytic destruction of stratospheric ozone, especially over the Antarctic, producing seasonal “ozone holes” and raising global concern about elevated surface UV-B fluxes (WMO & UNEP, 2022). The international response, embodied in the Montreal Protocol on Substances that Deplete the Ozone Layer and its subsequent amendments, is widely acknowledged as one of the most successful global environmental agreements, having substantially curtailed production and atmospheric abundance of regulated ozone-depleting substances (ODSs) and setting the world on a trajectory toward ozone recovery (Egorova et al., 2023; WMO & UNEP, 2022).

The global perspective, however, conceals important national and subnational heterogeneity in implementation. International agreements establish obligations and timelines, but realization at the country level depends on regulatory architecture, enforcement capacity, industry structure, finance, and the presence of informal sectors that reuse and trade refrigerants outside formal controls. Recent programmatic documents for developing countries show mixed performance: many developing-country hydrofluorocarbon/HCFC phase-out management plans (HPMPs) have achieved notable reductions in reported consumption of controlled substances through technical assistance and funding mechanisms, yet recurring implementation issues, insufficient customs controls, inadequate technician training, limited access to low-GWP alternatives, and persistent informal recycling and illegal trade, remain obstacles (Multilateral Fund Secretariat, 2023; UNDP Nigeria HPMP documents, 2019–2023). In Nigeria, the HPMP stages and associated progress reports illustrate both the potential of coordinated donor-supported initiatives and the practical constraints of national regulatory systems confronting complex refrigeration markets and resource limitations (Multilateral Fund Secretariat, 2023; UNDP, 2023).

The environmental and human health consequences of incomplete or uneven ODS phase-out remain material. Elevated UV-B irradiance, which would accompany sustained ozone depletion, elevates skin-cancer incidence, cataracts, and broader immune suppression, and can reduce crop yields and alter plant–pest dynamics with downstream effects on food security and rural livelihoods (Grant et al., 2024; Liaqat et al., 2023). Experimental and field studies over the last five years continue to document UV-B effects on plant physiology and phenology, reinforcing the conclusion that shifts in stratospheric ozone pose measurable risks to agriculture and biodiversity (Mathur et al., 2024; Liaqat et al., 2023). The dual environmental challenge —protecting stratospheric ozone while avoiding climate-intensive substitutes —therefore demands integrated policy responses that reconcile ozone protection, climate mitigation, and safe technology transitions (Liu et al., 2024; Park et al., 2021).

Despite these successes, the scientific record from 2020–2025 shows that the ozone problem has evolved rather than resolved: atmospheric trends reveal substantial declines in many classical ODSs but also underscore emergent challenges, including the large legacy “banks” of fluorocarbons in equipment and foams, episodic emissions from unexpected sources, and the climate trade-offs associated with replacement refrigerants (Egorova et al., 2023; Liu et al., 2024). Chemistry, climate model experiments demonstrate that without the Montreal Protocol’s constraints, the atmospheric burden of halogenated substances would have produced far larger ozone losses and substantial climate perturbations through direct radiative forcing; conversely, the Protocol’s regulations have avoided major ozone depletion and contributed important co-benefits for climate regulation (Egorova et al., 2023). However, the transition away from ozone-depleting chemistry has not been frictionless. Many of the commonly adopted substitutes, hydrofluorocarbons (HFCs), do not harm the stratosphere but are potent greenhouse gases; the Kigali

Amendment (2016) added the HFC phasedown to the Protocol precisely to mitigate this climate risk, and recent economic and climate assessments find that expedited reduction of HFCs yields very large social and climate benefits (Tan, Rennels, & Parthum, 2024; Park et al., 2021).

These cross-scale dynamics produce several pressing policy questions. First, while global scientific assessments (e.g., WMO & UNEP's 2022 Scientific Assessment) indicate that the atmospheric concentrations of many regulated ODSs have declined and that the ozone layer is on a long-term recovery trajectory, modelling and observational studies also highlight uncertainties and potential sources of delay in recovery that are traceable to national-level shortcomings in monitoring and enforcement (Egorova et al., 2023; WMO & UNEP, 2022). Second, the post-Kigali landscape has shifted the problem set: banks of fluorocarbons and incomplete lifecycle management imply time-lagged emissions that can substantially increase cumulative greenhouse forcing unless best practices for reclamation, safe disposal, and low-GWP adoption are widely implemented (Liu et al., 2024). Third, the human and ecosystem consequences of residual or episodic ozone depletion are not equally distributed, with vulnerable populations (e.g., outdoor workers, agricultural communities) and lower-resource countries facing disproportionate exposure and adaptation burdens (Grant et al., 2024).

This paper, therefore, adopts a critical assessment lens that traces the chain of events from global agreement to national practice. The primary objective is to evaluate the environmental implications of ODS and their substitutes by synthesizing authoritative secondary data—peer-reviewed scientific assessments, empirical modelling studies, international program documents, and national HPMP reports, to identify where global mitigation strategies have succeeded, where gaps remain, and what policy approaches best reconcile ozone protection with climate co-benefits. The study is driven by three research questions: (1) To what extent have global mitigation frameworks (Montreal Protocol and amendments, including Kigali) reduced atmospheric ODS burdens and shaped projected ozone recovery? (2) How effectively have national mitigation strategies and HPMP implementations translated global commitments into measurable reductions in ODS use and emissions, especially in countries with constrained enforcement and large informal sectors? (3) What policy interventions and governance mechanisms can most cost-effectively close remaining gaps, minimize climate trade-offs from substitutes, and protect vulnerable human and ecological systems?

The significance of this analysis is twofold. Scientifically, it integrates the most recent synthesis and modelling literature (2020–2025) showing both progress and remaining uncertainty in ozone recovery and fluorocarbon-related climate forcing (Egorova et al., 2023; Liu et al., 2024; Tan et al., 2024). Practically, it offers policy-relevant recommendations for national authorities and multilateral funders who must prioritise interventions—customs strengthening, technician certification, reclamation infrastructure, and incentives for low-GWP technologies—that are informed by secondary evidence and are implementable within the funding and institutional constraints typical of developing countries (Multilateral Fund Secretariat, 2023; Park et al., 2021). The following sections describe the desk-based methodology, present synthesized results from global and national secondary sources, and end with policy prescriptions aimed at securing both ozone recovery and climate co-benefits.

2. Conceptual Framework

Ozone-Depleting Substances (ODS)

Ozone-depleting substances are human-made halogenated chemicals that emit reactive chlorine or bromine atoms in the stratosphere, which catalyse the destruction of ozone (Villamayor et al., 2023). Their significance is assessed through various quantitative metrics, such as atmospheric lifetime, ozone-depletion potential (ODP), and global-warming potential (GWP). Additionally, substantial "banked" reserves of equipment and foams pose ongoing risks of future emissions (Chipperfield, 2024).

Ozone depletion

The reduction of the stratospheric ozone layer, known as ozone depletion, diminishes the protective barrier against ultraviolet-B (UV-B) radiation, increasing vulnerability for both humans and ecosystems. This variable acts as a mediating link: ODS emissions influence ozone depletion, which, in turn, affects the dependent outcomes. Recent studies indicate that, although signs of recovery are present, new challenges, including very short-lived halogenated substances (VSLS) and extraordinary natural events, continue to threaten this recovery trajectory (Chipperfield, 2024; Dreyfus et al., 2024). The extent and regional variation of ozone depletion are vital for understanding the differing risks across regions.

Environmental and Human-Health Implications

Increased UV-B exposure resulting from ozone depletion causes various environmental and health effects, including higher rates of skin cancer, cataracts, immune suppression, reduced crop yields and plant productivity, and disruptions to marine ecosystems (Neale et al., 2025). The outcomes serve as the dependent variable within the conceptual framework. The severity of impacts depends on exposure levels, adaptive capacity, and geographic factors such as latitude, cloud cover, and population vulnerability.

Global Mitigation Strategies

Global mitigation strategies encompass multilateral agreements and institutional frameworks designed to interrupt the connection between ODS and ozone depletion. The Montreal Protocol on Substances that Deplete the Ozone Layer and its amendments exemplify a global governance system that phases out the production and use of ozone-depleting substances, promotes alternatives, and supports capacity-building in lower-income countries (Perry, 2024). Research highlights the Protocol's success, while also stressing the need for further investigation into substitute management and residual emissions (Perry, 2024).

National Implementation Capacity

National-level implementation capacity includes regulatory enforcement, monitoring and data collection systems, informal sector control, financial and technical support, and industry compliance. This variable affects the effectiveness of global mitigation strategies. Despite international commitments, outcomes vary due to differences in national capacity (Perry, 2024). Countries with weak customs controls, limited technician training, and large informal refrigerant sectors show slower progress in phase-out efforts. Therefore, the capacity to implement measures impacts how well global strategies achieve national emission reductions.

Substitutes and Trade-Offs

With the phase-out of ozone-depleting substances (ODS), alternative substances such as hydrofluorocarbons (HFCs) and hydrofluoro-olefins (HFOs) are being adopted for industrial uses. Many substances show minimal ozone-depletion potential; however, they may possess significant global-warming potential and contribute to secondary climate risks (van den Oever et al., 2024). Lifecycle analyses emphasise the importance of addressing banked volumes, disposal practices, and unintended releases of substitutes to fully understand the mitigation outcomes.

3. Theoretical Framework

Multi-Level Perspective (MLP)

This study employs the Multi-Level Perspective (MLP) as the main theoretical framework to analyse the transition from ozone-depleting substances (ODS). The Multi-Level Perspective (MLP), formulated by Frank W. Geels in 2002, explains socio-technical change through interactions among niches, socio-technical regimes, and the broader landscape context. Niche innovations such as low-GWP refrigerants and reclamation systems aim to challenge traditional industrial practices and regulatory frameworks, while global pressures, including the Montreal Protocol and scientific climate assessments, significantly influence national systems (Geels, 2002; Geels, 2011). This framework clarifies the reasons for the uneven progress in phasing out ODS, emphasising technological lock-in, market behaviour, and infrastructure dependence that hinder regime transformation. Recent advancements in the theory improve its focus on agency and actor strategies, thereby increasing its relevance for real-world transitions (Geels, 2020). MLP is particularly suited for this study, as it aligns with the technological and institutional changes required to eliminate ODS and prevent problematic substitutes. This analysis assesses Nigeria's national ozone management system's response to external pressures and its adaptation of available innovations. At the same time, there are inherent limitations; the framework insufficiently addresses power dynamics and enforcement issues within national systems. The analytical categories pose challenges in operationalisation with secondary data and offer minimal normative guidance for strengthening governance capacity.

Polycentric Governance Theory

Polycentric Governance Theory is utilised as a complementary perspective to address these gaps. Elinor Ostrom's research highlights that environmental issues are managed by overlapping authorities that must collaborate for successful outcomes (Ostrom, 2010). This observation pertains to the layered compliance framework of the Montreal Protocol, in which international agencies, national regulators, customs authorities, industries, and technicians collectively assume responsibility for refrigerant management. The theory emphasises the importance of subnational experimentation, institutional monitoring, and capacity asymmetries in influencing implementation outcomes (Kellner, 2024). Polycentric systems may experience fragmentation, disparities in resource allocation, and ambiguity in accountability.

The two theories together provide a comprehensive framework for this study. The MLP elucidates the dynamics of technological transitions, whereas polycentric governance addresses challenges related to institutional performance and coordination. Their integration enhances the analytical capacity of the seminar paper to assess Nigeria's mitigation strategies, identify enduring regime barriers, and clarify governance pathways that promote compliance with the Montreal Protocol.

Empirical Review

Global mitigation progress

Recent observational and modelling evidence indicates that global mitigation efforts under the Montreal Protocol have significantly altered the trajectory of ozone-depleting substances (ODS) and have positioned the ozone layer on a broadly positive recovery path. Long-term measurement networks and repeated scientific assessments show persistent declines in many legacies' ozone- depleting substances, consistent with the Protocol's phased reductions in production and consumption. The WMO/UNEP Scientific Assessment of Ozone Depletion (2022) synthesised atmospheric monitoring and modelling results and concluded that, under current policy trajectories, the global ozone layer is expected to recover in the coming decades. However, the timing varies by latitude and region (WMO & UNEP, 2022). The assessment acts as the definitive reference for analysing recent trends.

Empirical monitoring confirms the assessment's main conclusions. Global measurement programmes, especially NOAA's long-term flask, in-situ, and remote sampling networks, show a decline in traditional chlorofluorocarbons (e.g., CFC-11, CFC-12) and numerous HCFCs since their peak regulatory periods (NOAA GML, 2024). Recent analyses of oceanic and atmospheric CFC inventories reveal decreases in surface-ocean concentrations of CFC-11 and CFC-12 that align with atmospheric declines, with reductions of about 10–20% since their peaks in the 1990s– 2000s (Lester et al., 2024). The consistent observational evidence increases confidence that emissions controls implemented under the Montreal Protocol have lowered atmospheric levels of key regulated ozone-depleting substances (ODS). Counterfactual experiments based on models evaluate the extent of the Protocol's benefits. Simulations using Earth-system models comparing "with-Protocol" and "no-Protocol" scenarios suggest that the absence of Protocol controls would lead to significantly greater ozone depletion and higher radiative forcing. Therefore, the restrictions introduced by the Protocol have effectively prevented substantial stratospheric halogen build-up and related ozone loss, while also delivering measurable climate co-benefits (Egorova et al., 2023). Model syntheses indicate that the Protocol not only decreased atmospheric concentrations of ODS but also markedly influenced projected ozone recovery, resulting in earlier restoration timelines and reduced severity of worst-case ozone depletion.

Recent literature simultaneously highlights qualifications and the evolving challenges faced. Chipperfield (2024) and others note that although the overall recovery trajectory remains favourable, episodic disturbances, such as volcanic aerosol injections and significant wildfires, along with increases in emissions from unforeseen or underreported sources, may cause temporary regional setbacks. The resurgence of detectable unexpected emissions episodes in recent years underscores the ongoing need for global monitoring and enforcement vigilance (Chipperfield, 2024). The presence of substantial banked stocks of fluorocarbons in equipment and foams results in time-lagged emissions, thus extending the timeframe for realising mitigation benefits. Dynamic material-flow analyses suggest that banked substances, if not actively reclaimed or destroyed, can produce considerable cumulative GWP-weighted emissions through mid-century. Implementing best-practice management can significantly reduce these projected emissions (Liu et al., 2024). The most recent evidence, including observational networks, ocean tracer studies, and Earth- system modelling, tells a consistent story: the Montreal Protocol has worked to lower the levels of the most harmful ODS in the atmosphere and put the ozone layer on a path to recovery, while still being sensitive to short-term changes and the long-term effects of stored substances. The literature thus recontextualises the current policy challenge as one of continuous vigilance: ensuring comprehensive oversight, addressing deficiencies in illegal production and trade, and regulating banks and alternatives to guarantee both ozone recovery and the climate co-benefits that the Protocol can provide (WMO & UNEP, 2022; Egorova et al., 2023; Liu et al., 2024; Lester et al., 2024; NOAA GML, 2024).

National implementation cases

National experiences in implementing HCFC phase-out management plans (HPMPs) show that there have been significant drops in reported use of prohibited substances, but there are still problems with enforcing, monitoring, and managing legacy "banks." HPMPs include investment- stage conversion projects, regulatory measures, strengthened customs controls, and capacity building in the service sector. The results depend heavily on a country's wealth, its industrial structure, and the effectiveness of its institutions (Multilateral Fund Secretariat, 2024).

Nigeria

Nigeria's HPMP indicates progress in reducing reported HCFC use through phased tranches and targeted investments. However, official project records clearly reveal ongoing implementation challenges. UNDP/UNIDO project documents for Nigeria (HPMP Stage II and Stage III tranche reports and related files) show that conversion projects in foam and refrigeration manufacturing have been completed. They also demonstrate that HCFC-141b and HCFC-22 consumption have decreased compared to baseline years, and that Multilateral Fund resources have been allocated to support industry conversion and training for the servicing sector (UNDP Nigeria HPMP; UNIDO project tranches). Conversely, Executive Committee papers and tranche reports highlight persistent gaps in enforcement at ports of entry, difficulties customs face in identifying all shipments, and a significant level of informal sector activity, which complicates tracking actual emissions versus reported consumption (UNDP/UNIDO Nigeria HPMP documents; Multilateral Fund project proposals). In short, Nigeria exemplifies a recurring pattern: genuine progress is being made on paper, yet obstacles remain due to inadequate monitoring and informal flows.

India

The HPMP trend in India indicates that industrial conversion is accelerating, but the demand for goods and services remains quite complex. Stage-wise HPMP documentation (Government of India / Ozone Cell HPMP Stage II/III materials) shows that the government is making significant investments in upgrading manufacturing lines, particularly in the room air-conditioning and refrigeration sectors, and in establishing new licensing and reporting systems. Project proposals and materials from the Executive Committee detail how some companies are transitioning from HCFC-22 to lower-ODP/HFC-32 lines, supported by grants to improve technology. Simultaneously, national initiatives have helped technicians obtain certification and adhere to servicing regulations to reduce emissions (Ozone Cell, India; Multilateral Fund project proposals). However, evaluation papers highlight the challenges of monitoring small-scale producers and informal service technicians across regions, as well as the necessity to ensure conversions focus on low-GWP options to avoid climate trade-offs. India has a large industrial sector and numerous businesses yet ensuring that all products across markets offer low-GWP alternatives remains difficult.

China

China's experience with HPMP demonstrates that it is both a major producer and user of HCFCs and that it can manage large, technically complex conversion operations. Reports from the World Bank and the Multilateral Fund on China's HPMP and production sector programmes indicate a systematic shift in foam and refrigeration manufacturing, with strict reporting and the achievement of several consumption-phase targets ahead of schedule. The World Bank's implementation and results reports illustrate that structured project management, measurable HCFC reductions in targeted sub-sectors, and the incorporation of HCFC phase-out goals into national industrial policy are all feasible. However, they also emphasise that careful management is essential to prevent displacement effects and to address residual production for non-controlled uses (World Bank implementation reports; UNEP country profile). China's example highlights how strong institutional capacity and the alignment of industrial policy can accelerate the phase-out process. Nonetheless, diligent oversight is necessary to navigate the complex repercussions across the production chain.

A comparative analysis of these three situations reveals consistent features. First, HPMPs demonstrate proven reductions in reported HCFC consumption, with investment components focused on manufacturing conversion and servicing-sector training; records from the Multilateral Fund and implementing agencies verify many tranche-level successes (Multilateral Fund

Secretariat; UNDP/UNIDO project documents). Second, enforcement challenges, such as limited customs screening capabilities and the existence of informal service markets, remain significant barriers to halting illegal trade and unexpected emissions (project reports for Nigeria and India frequently highlight customs and informal-sector issues). Third, scale is important: large manufacturing countries like India and China can implement conversion technology on a considerable scale but must be cautious in selecting replacements to avoid high-GWP alternatives. Smaller or resource-limited countries require additional support from the Multilateral Fund to achieve outcomes similar to those of the phase-out. Overall, national HPMP documentation and Executive Committee evaluations provide a reliable secondary data basis for assessing implementation performance, as they include audited consumption reports, tranche completion certificates, and project evaluations.

Policy instruments

Various policy instruments have been implemented at both global and national levels to facilitate the elimination of ozone-depleting substances (ODS) and to promote the adoption of safer alternatives. Key measures include legal prohibitions and licensing frameworks governing the production, import/export, or utilisation of ODS; training programmes for technicians to ensure the safe handling and servicing of refrigerants; financial subsidies and incentive schemes to support industry transition; and technology transfer initiatives aimed at advancing low-global- warming-potential (GWP) alternatives (UNEP, 2025; UNIDO, 2023). Project documents associated with the Montreal Protocol's Multilateral Fund indicate that investment initiatives in Article 5 countries frequently encompass integrated legal and regulatory measures alongside financial support for foam-sector conversion, equipment servicing enhancements, and technician certification (Multilateral Fund Secretariat, 2024). However, the literature indicates variability in instrument uptake and a necessity for coherent policy mixes: certain national HPMPs emphasise conversion subsidies while inadequately investing in enforcement and licensing systems, thereby undermining the compliance chain (UNIDO, 2023). The policy-instrument variable serves as a crucial framework for assessing the effectiveness of various combinations in converting global treaty obligations into national implementation results.

Persistent challenges

Despite recorded progress, substantial hurdles remain that impede the full and swift elimination of ODS and their alternatives. A recurring issue is the illegal trade and unreported production of controlled substances, which various monitoring studies (e.g., atmospheric fluorocarbon anomalies) suggest may distort reported national consumption figures (COP Alliance, 2023). Furthermore, the slow uptake of safer, low-GWP alternatives is often attributed to cost challenges, gaps in service-sector expertise, uncertainties about safety and regulatory standards (such as flammability and toxicity), and resistance in traditional equipment markets (Tan et al., 2024). The absence of robust monitoring infrastructure poses a significant obstacle: many developing countries rely on self-reported consumption data and lack systematic atmospheric tracking or refrigerant reclamation systems, resulting in inadequate records of informal servicing and stored refrigerants (UNEP, 2025). Market resistance due to established technologies embedded in existing refrigerant systems, imports of used equipment, and servicing networks supporting older refrigerants further hampers transition efforts (COP Alliance, 2023). These challenges highlight that, despite policy frameworks, operational and structural barriers still impede full national compliance and compromise environmental outcomes.

Co-benefits and trade-offs

The shift from ODS mandated by the Montreal Protocol has yielded significant environmental co- benefits; however, the literature highlights notable trade-offs. Reductions in ODS have positively influenced both ozone recovery and climate mitigation by preventing radiative forcing from halogenated chemicals (Egorova et al., 2023). Nonetheless, the transition to hydrofluorocarbons (HFCs) as replacements has posed a climate challenge: many HFCs have high global warming potentials (GWPs) and increase the risk of greenhouse gas emissions, thereby undermining net environmental benefits unless low-GWP alternatives are adopted (Tan et al., 2024; NRDC, 2024). Recent studies suggest that if HFC emissions continue unabated, a substantial portion of the climate benefits from ozone policies may be lost (Wu et al., 2025). The literature highlights that achieving both ozone protection and climate benefits requires policies that promote safe, low-GWP substitutes, upgrade to energy-efficient equipment, and actively manage legacy refrigerant banks (UNEP, 2025). The co-benefit/trade-off variable illustrates the dual challenge of advancing ozone protection whilst reducing climate impact.

4. Methodology

This seminar paper employs a qualitative research design using secondary data to evaluate the environmental impacts of ozone-depleting substances (ODS) and the effectiveness of mitigation strategies. Secondary-source analysis is suitable for environmental studies where substantial scientific data is already available (Snyder, 2019). Data were collected from peer-reviewed journal articles, international reports, and national policy documents issued by reputable institutions such as UNEP and WMO between 2020 and 2025 to ensure current relevance. A systematic search was conducted using key terms such as “ozone depletion,” “Montreal Protocol,” “ODS phase-out strategies,” and “Nigeria ozone governance” across Google Scholar, Scopus, and ScienceDirect.

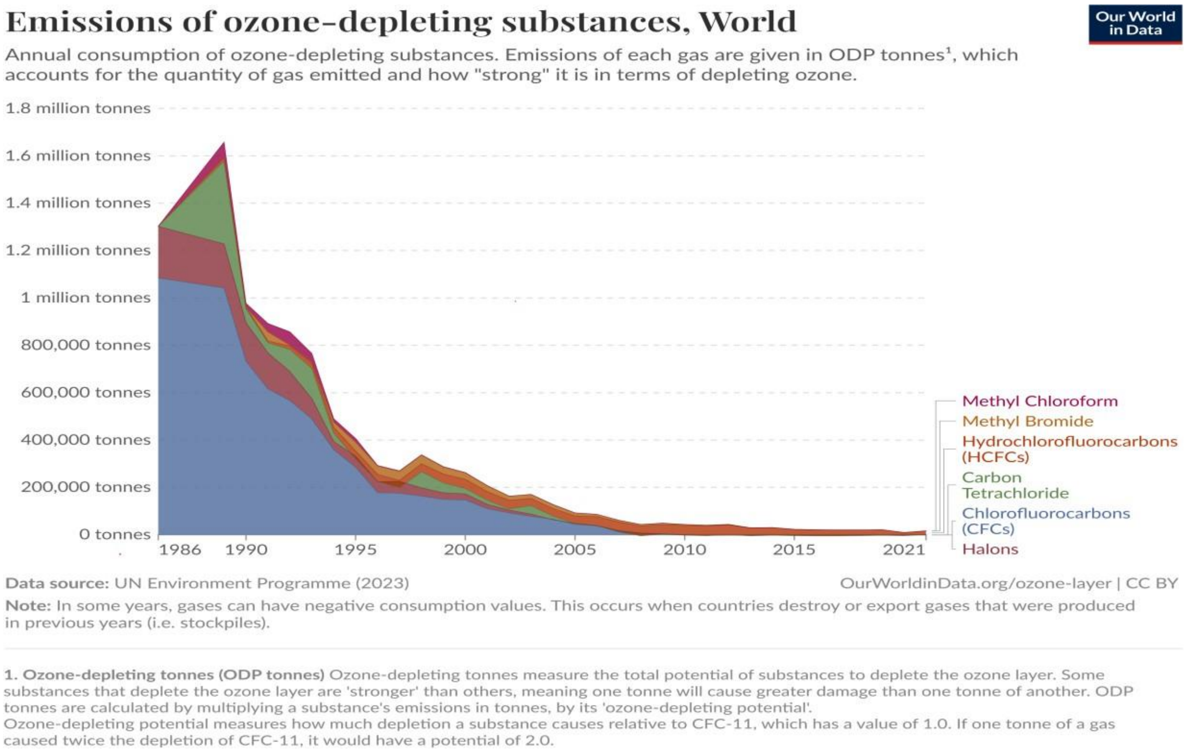
5. Discussion

This study's findings revealed a dual narrative: significant global advances in ozone protection alongside enduring national vulnerabilities that persist as environmental and climate risks. Recent scientific assessments provide evidence that the Montreal Protocol has substantially decreased atmospheric levels of classical ozone-depleting substances, leading to noticeable trends in ozone- layer recovery (WMO & UNEP, 2022; Egorova et al., 2023). National case studies, particularly in developing economies like Nigeria, reveal that the execution of mitigation strategies is hindered by inadequate regulatory enforcement capacity, the presence of informal refrigerant markets, and deficiencies in customs surveillance systems. The findings correspond with current research indicating that although HPMPs have documented significant reductions in controlled substance use, actual emissions frequently differ due to unaccounted leakage and illegal trade (Chipperfield, 2024; Multilateral Fund Secretariat, 2024). The existence of informal servicing networks in Nigeria underscores the significance of Polycentric Governance Theory, which suggests that fragmented authority may diminish compliance outcomes in the absence of adequate coordination structures (Kellner, 2024).

The discovery that fluorocarbon reserves in outdated equipment and foams pose a significant future emissions risk indicates a growing agreement that policy focus should extend beyond production regulations to encompass lifecycle management. Recent studies on material flows indicate that unrecovered legacy stocks could significantly contribute to cumulative emissions through 2050, jeopardising progress on ozone and climate if not systematically reclaimed or destroyed (Liu et al., 2024).

Another important finding relates to substitution trade-offs. While HFCs mitigate ozone depletion, their significant global-warming potentials pose climate risks that could undermine the co-benefits of the Protocol (Tan et al., 2024). The Kigali Amendment addresses this challenge; however, the study indicates that adoption of low-GWP alternatives remains inconsistent, especially in low- income contexts where financial and technical constraints impede the transition (UNEP, 2025). The findings support recent assessments that highlight the need for cohesive policies explicitly linking ozone governance to climate mitigation (Wu et al., 2025).

Additionally, the implications for ecology and human health are urgent. The results indicate that intermittent ozone-depletion events and insufficient phase-outs sustain UV-B exposure risks, disproportionately impacting agricultural communities and outdoor workers in the Global South. Recent research indicates that UV-B exposure induces physiological stress in food crops and increases morbidity risks in populations with high exposure (Grant et al., 2024; Neale et al., 2025). The findings highlight the significance of addressing distributional equity, as the advantages of ozone recovery are distributed globally, whereas the remaining harms are concentrated locally. The findings suggest a changing policy landscape: the ozone challenge now encompasses not only the reduction of controlled ODS but also the enhancement of governance systems in countries with capacity deficiencies, the assurance of scientifically validated low-GWP alternatives, and the prioritisation of environmental justice. This is consistent with the Multi-Level Perspective framework, which predicts uneven regime transitions resulting from technological lock-in and institutional inertia (Geels, 2020). Enhancing national enforcement, refining data systems, and augmenting investment in technician training and refrigerant recovery processes would significantly expedite progress. The findings indicate a cautiously optimistic outlook. The global governance architecture is functional; however, its success now hinges on addressing the remaining implementation gaps. Addressing the enforcement weaknesses, substitution trade-offs, and legacy-bank risks identified in the study will enable the Montreal Protocol and its Kigali Amendment to function effectively as dual-benefit instruments for ozone recovery and immediate climate protection.



Emissions of ozone-depleting substances, World

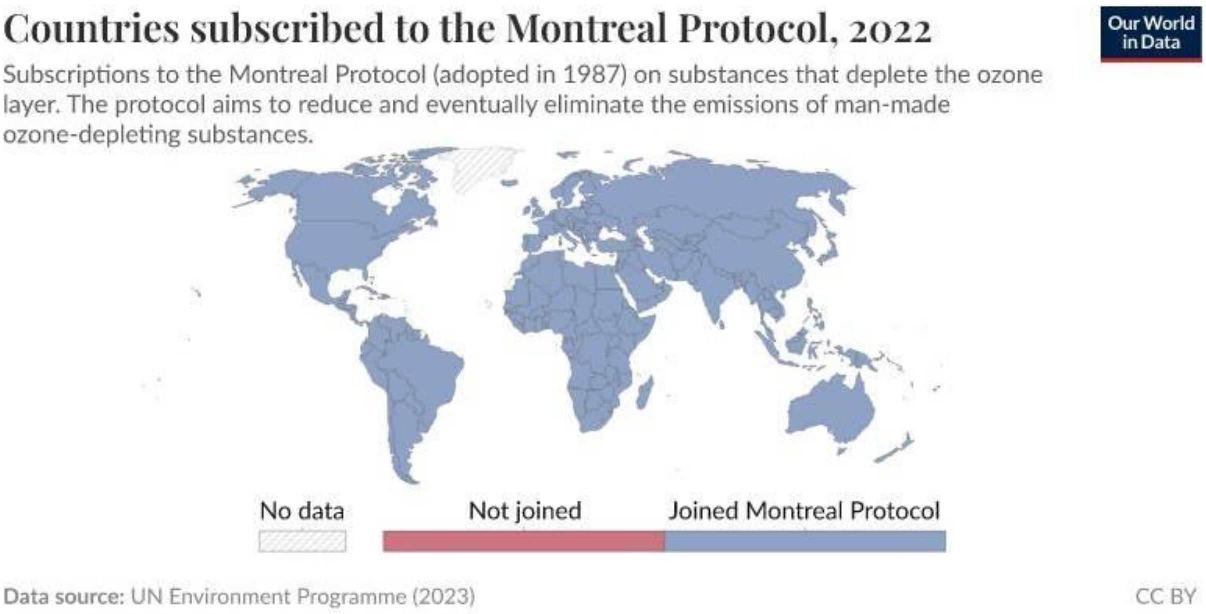
Annual consumption of ozone-depleting substances. Emissions of each gas are given in ODP tonnes[1], which accounts for the quantity of gas emitted and how "strong" it is in terms of depleting ozone.

Data source: UN Environment Programme (2023) OurWorldinData.org/ozone-layer | CC BY

Note: In some years, gases can have negative consumption values. This occurs when countries destroy or export gases that were produced in previous years (i.e. stockpiles).

1. Ozone-depleting tonnes (ODP tonnes) Ozone-depleting tonnes measure the total potential of substances to deplete the ozone layer. Some substances that deplete the ozone layer are 'stronger' than others, meaning one tonne will cause greater damage than one tonne of another. ODP tonnes are calculated by multiplying a substance's emissions in tonnes, by its 'ozone-depleting potential'.
Ozone-depleting potential measures how much depletion a substance causes relative to CFC-11, which has a value of 1.0. If one tonne of a gas caused twice the depletion of CFC-11, it would have a potential of 2.0.

Figure 1. Emissions of Ozone-Depleting Substances.

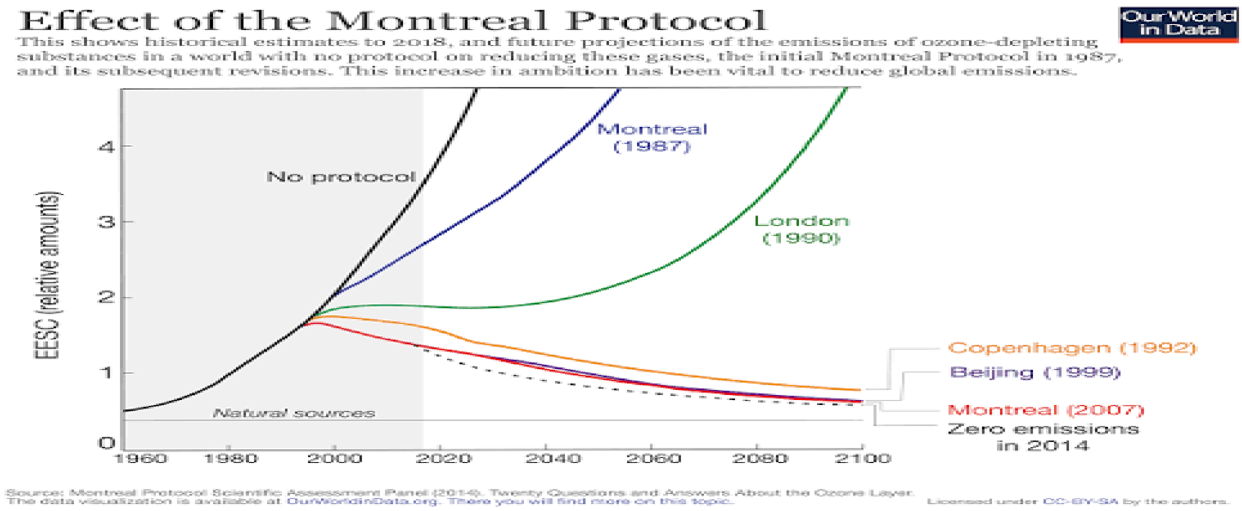


Countries subscribed to the Montreal Protocol, 2022

Subscriptions to the Montreal Protocol (adopted in 1987) on substances that deplete the ozone layer. The protocol aims to reduce and eventually eliminate the emissions of man-made ozone-depleting substances.

Data source: UN Environment Programme (2023) CC BY

Figure 2: Countries Subscribed to the Montreal Protocol



Source: Montreal Protocol Scientific Assessment Panel (2014). Twenty Questions and Answers About the Ozone Layer.
The data visualization is available at OurWorldinData.org. There you will find more on this topic.
Licensed under CC-BY-SA by the authors.

Figure 3: Effect of the Montreal Protocol.

The OWID chart illustrating the cumulative number of states that have signed the Vienna Convention and the Montreal Protocol serves as a significant visual representation of the widespread global commitment to the ozone-layer protection framework. The substantial increase in state participation from the early 1990s to the 2000s, followed by stabilisation at approximately 198 parties, supports the assertion that the Montreal Protocol achieved an extraordinary level of treaty universality. The universality of this principle underpins the strong collective governance framework that has facilitated the observed global reductions in ozone-depleting substances (ODS) (Egorova et al., 2023). The rapid adoption of parties, viewed through a governance-theoretical lens, aligns with the "landscape" level within the Multi-Level Perspective (MLP) framework, reflecting a global trend that exerts pressure on national regimes to adapt. The high rate of ratification indicates robust legitimacy and widespread normative expectations, likely increasing compliance pressures on national governments. However, the near-universal participation does not guarantee consistent implementation effectiveness, as the findings of the national case study emphasise.

At the national level, findings suggest that although many countries have established legal frameworks and reported substantial reductions in HCFC consumption through staged HPMPs, results vary considerably. In Nigeria, project reports indicate documented reductions in the use of HCFC-141b and HCFC-22; however, ongoing enforcement gaps at ports and within the informal sector remain a challenge. This demonstrates that treaty ratification, as shown in the OWID graph, is a necessary but not sufficient condition for effective national implementation. While the large number of ratifications provides a strong foundation, it also masks significant differences in implementation capacity and the robustness of governance systems.

The graph shows a notable shift in the challenge, from securing participation to guaranteeing effective implementation and transformative change within national regimes. The focus of governance moves from how to include countries in the treaty to how to change behaviour, markets, and emissions within those countries' regimes. The findings reveal that national capacity for customs controls, technician training, and monitoring of banked refrigerant stocks varies, even among treaty-compliant states. Visual evidence of global adoption strengthens the credibility of the previously mentioned progress in mitigation. Trends showing declining atmospheric ODS levels and advancing ozone-recovery paths are further supported by the near-universal participation in treaties. However, this universality exposes the issue of governance saturation: once all states are involved, further improvements rely on the quality of implementation rather than increasing membership. The core challenge is mainly one of regime transformation, not expanding membership.

The graph revealed an implicit temporal dimension: most parties joined by the early 2000s, indicating that the following decade focused on deepening rather than expanding the treaty. The observed improvements in ODS reduction and ozone recovery since 2020 now largely rely on national regime actions, substitute management, banked-stock reclamation, and informal-sector controls, rather than on new signatories or formal treaty milestones. The graph highlights the transition described in the findings: a global regulatory framework is largely in place, and current progress depends on the effectiveness and strength of national implementation and technical infrastructure.

6. Conclusion

This study demonstrates that the Montreal Protocol has effectively reduced atmospheric levels of key ozone-depleting substances, promoting the recovery of the ozone layer. However, implementation at the national level remains inconsistent. Nigeria faces ongoing challenges, including informal refrigerant markets, limited enforcement capacity, inadequate technician training, and poor management of legacy fluorocarbon banks. These constraints hinder the full phase-out of ODS and lead to climate trade-offs from the continued use of high-GWP substitutes. Achieving full ozone recovery and climate co-benefits depends on strengthening governance systems, adopting low-GWP technologies, and prioritising equitable protection for vulnerable populations disproportionately impacted by UV-related risks. Continued vigilance and capacity-building are vital for turning global commitments into lasting national environmental outcomes. Future research should explore advanced monitoring technologies, such as real-time atmospheric detection and digital refrigerant-tracking systems, to more accurately quantify unreported emissions. Additional research emphasising equitable access to low-GWP alternatives in developing countries would further enhance the effectiveness and inclusivity of efforts to recover the ozone layer.

7. Recommendation

Strengthening national enforcement and monitoring systems is essential to ensure that regulatory commitments result in quantifiable environmental outcomes. Improved customs surveillance, refined licensing frameworks, and robust refrigerant-tracking systems would help eradicate illegal trade and minimise discrepancies between reported and actual emissions. Enhanced interagency coordination and transparent data systems are critical for ensuring compliance.

To mitigate the climate penalties associated with high-GWP substitutes, it is essential to expedite the adoption of low-GWP technologies and to strengthen enforcement measures. Financial incentives, targeted technology transfer, and expanded technician certification will facilitate manufacturers and service professionals transitioning to safer alternatives. This transition necessitates the acquisition of new equipment and the development of practical skills to reduce leakage and maintain sustainable operation across the lifecycle of cooling systems.

With the introduction of low-GWP technologies, it is crucial to focus on the safe management of existing "banked" refrigerants to reduce future emissions. Developing structured programmes for reclamation, recycling, and destruction will help prevent delayed releases from ageing appliances and foam insulation. It is also vital to encourage participation from both the formal industry and the informal servicing sector to effectively capture refrigerants that might otherwise be released into the atmosphere.

Mitigation efforts must align with broader climate change and public health goals to maximise societal benefits. Integrated policy frameworks that address UV exposure risks, the climate effects of substitute chemicals, and the vulnerabilities of outdoor-dependent communities will promote a more equitable distribution of environmental benefits whilst protecting those who continue to face increased health risks.

Maintaining this progress requires increased international support, particularly for developing economies with limited technical and financial resources. Greater support from the Multilateral Fund, focusing on institutional strengthening, technology transfer, and implementation logistics, will help countries such as Nigeria meet phase-out obligations and achieve sustained ozone recovery alongside climate co-benefits. The integration of these strategies can help translate global ozone governance achievements into sustainable national environmental protection.

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