

Strategies for Managing Perfluorinated Compounds (PFCs) in Semiconductor Manufacturing: A Supply Chain and Public Management Approach

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Abstract. The semiconductor industry stands as a pillar of modern technological progression, yet it grapples with significant environmental challenges, predominantly due to the emissions of perfluorinated compounds (PFCs). PFCs, critical in semiconductor manufacturing processes like dry etching and chemical vapor deposition (CVD) chamber cleaning, present a dire environmental concern given their high Global Warming Potential (GWP) and persistent nature. This treatise delves into a comprehensive analysis of how supply chain management and astute public policy can mitigate the deleterious impact of PFCs. It methodically scrutinizes the current challenges in curbing these emissions, assesses the efficacy of prevailing strategies, and champions the inception of trailblazing abatement technologies alongside forward-thinking regulatory frameworks. The research presents a critical evaluation of the interplay between stringent environmental requirements and the semiconductor industry's economic and innovation imperatives. It underscores the intricacies of aligning the sector's operations with sustainable practices while maintaining its economic vitality and capacity for innovation. Through a meticulous exploration of advanced material alternatives, state-of-the-art emissions control technologies, and progressive policy initiatives, this paper endeavors to steer the semiconductor industry towards a future where environmental sustainability becomes a cornerstone of its developmental ethos without stifling its technological evolution or economic robustness.

Keywords: Semiconductor Manufacturing, Perfluorinated Compounds (PFC) Emissions, Environmental Management, Supply Chain Strategies, Public Policy, Abatement Technologies.

1. Introduction

The semiconductor industry stands as a pillar of modern technological progress, bridging the gap between theoretical innovation and practical application. Semiconductors, which possess electrical conductivities that fall between insulators and conductors, are the cornerstone of a myriad of devices critical to advancing global industrial and economic growth. From powering the rapidly evolving landscapes of 5G technology, the Internet of Things (IoT), to Artificial Intelligence (AI), big data,



and cloud computing, semiconductors are indispensable in the fabric of contemporary life. The exponential growth of the semiconductor industry, particularly in the high-tech sectors, necessitates an evolution in production techniques that are both efficient and environmentally conscious. As the industry surges, so does the environmental footprint, marked notably by the emission of carbon oxides and perfluorinated compounds (PFCs) [1]. These gases, while integral to the manufacturing processes, pose significant environmental challenges. Carbon oxides, encompassing carbon dioxide (CO₂) and carbon monoxide (CO), are of particular concern. CO₂, a well-known greenhouse gas, traps heat in the Earth's atmosphere, contributing to global warming and ensuing climate change. On the other hand, CO is a toxic pollutant that compromises air quality and poses serious health risks to both humans and wildlife [2-4]. In the semiconductor manufacturing process, PFCs gases are emitted, which are potent greenhouse gases with long atmospheric lifetimes and high global warming potentials. The control and management of these emissions are not just a matter of corporate responsibility but a crucial public concern that intersects with global environmental sustainability goals. To this end, supply chain management within the semiconductor sector and public management have pivotal roles to play. Efficient supply chain strategies must be implemented to mitigate the impact of PFCs emissions, requiring the integration of green practices throughout the manufacturing and distribution processes. Concurrently, robust public management and policy-making efforts are essential to regulate and guide industries towards sustainable practices [3]. A significant environmental concern within semiconductor manufacturing is the use of perfluorinated compounds (PFCs). These chemical agents, vital for the etching and cleaning processes in semiconductor production, are potent GHGs with extraordinarily long atmospheric lifespans—estimated at up to 50,000 years for tetrafluoromethane (CF₄) and 10,000 years for hexafluoroethane (C₂F₆). Their global warming potentials are orders of magnitude greater than CO₂, with values of 6,630 for CF₄ and 11,100 for C₂F₆ over a 100-year horizon. This staggering longevity and high GWP underscore a pressing need for critical assessment and proactive management of PFC emissions [5]. This paper aims to explore the critical dynamics of supply chain and public management in controlling PFCs emissions in the semiconductor industry. It will delve into the implications for public health, environmental sustainability, and the mechanisms by which the industry can respond to these challenges through innovation, regulation, and proactive environmental stewardship.

2. The Role of PFCs in Semiconductor Manufacturing

2.1 PFCs in the Semiconductor Industry and Environmental Implications

Perfluorinated compounds (PFCs), widely utilized in the semiconductor industry due to their exceptional chemical stability and resistance to thermal decomposition, represent a dual-edged sword. While their properties are crucial for industrial processes, they also carry significant environmental implications. PFCs are characterized by a high Global Warming Potential (GWP)—substantially higher than that of CO₂—making them formidable contributors to climate change [6]. The durability that makes PFCs valuable in manufacturing leads to their extended atmospheric lifespan, which can result in near-irreversible environmental degradation. **Table 1** details the comparative GWPs of several greenhouse gases, highlighting the disproportionate impact of PFCs. Tetrafluoromethane (CF₄) and hexafluoroethane (C₂F₆) are primarily emitted during plasma etching and chemical vapor deposition processes. These compounds, along with other PFCs such as octafluoropropane (C₃F₈) and hexafluorobutadiene (C₄F₈), not only add directly to greenhouse gas concentrations but also participate in complex secondary reactions [7].

Given their persistent nature, PFCs represent a critical target for emissions management within the semiconductor industry's supply chain. Addressing PFC emissions entails a multifaceted approach, encompassing the design and adoption of more sustainable manufacturing technologies, improvements in supply chain transparency, and end-to-end lifecycle management [8]. Furthermore, effective public management, through stringent regulations and policy frameworks, is essential to enforce industry compliance, foster innovation in green chemistry, and encourage the adoption of

best practices that mitigate the release of these potent gases. The challenge is not merely to curtail the immediate release of PFCs but to understand and manage their lifecycle from production to end-of-life disposal [9].

Table 1. GWP values, by-products, and noteworthy remarks for the relevant gas categories [2].

Gas	GWP (IPCC 2019)	By-Product Sources (AR5)	Remark By-Product Sources (AR6)
CO ₂	1	-	-
CH ₄	28	-	-
N ₂ O	265	-	-
CHF ₃	12,400	CF ₄ , C ₂ F ₆ , C ₃ F ₈	CF ₄
CH ₂ F ₂	677	CF ₄ , CHF ₃	CF ₄ , C ₂ F ₆ , CHF ₃
CH ₃ F	116	-	C ₂ F ₆
CF ₄	6,630	-	C ₂ F ₆ , C ₃ F ₈ , CHF ₃ ; IPCC 2019 differentiate ThinFilm & Etching
C ₂ F ₆	11,100	CF ₄	CF ₄ , CHF ₃
C ₃ F ₈	11,000	CF ₄	CF ₄
C ₄ F ₈	9,450	CF ₄ , C ₂ F ₆	CF ₄
SF ₆	23,500	-	CF ₄ , C ₂ F ₆ , CHF ₃
NF ₃	16,100	CF ₄	CF ₄ (In-situ & Remote)

2.2 Utilization of PFCs in Semiconductor Manufacturing

Perfluorinated compounds (PFCs) are extensively utilized in the semiconductor industry for their essential roles in dry etching and chemical vapor deposition (CVD) chamber cleaning processes. As semiconductor devices continue to decrease in size, the demand for precise manufacturing techniques like dry etching increases due to its superior resolution compared to wet etching. This method involves using plasma or thermal energy to disintegrate perfluorinated gases into reactive species that selectively remove unwanted materials from the silicon wafer. CVD chamber cleaning represents another critical application of PFCs, where gases such as tetrafluoromethane (CF₄) are deployed to clean out residual deposits left from previous deposition cycles. However, the efficiency of these processes is limited; studies indicate that only about 20-40% of PFCs are effectively utilized in the etching process, while the remaining 60-70% are released as emissions during the cleaning of CVD chambers. The complexities of managing PFC emissions are compounded by the diversity of gases used across different manufacturing processes [10]. For example, etching operations may employ a variety of gases, necessitating a broad-spectrum approach to exhaust gas treatment. Conversely, CVD cleaning typically results in predominantly CF₄ emissions, thereby focusing abatement efforts on this specific compound. Addressing these emissions poses a significant challenge for the semiconductor sector. Effective management requires not only optimizing production processes to reduce the volume of PFCs used but also developing and implementing advanced abatement technologies capable of tackling a wide array of emissions. The situation is further complicated by the need for supply chain coordination to ensure that innovations in emission reduction are effectively integrated at all stages of production [11-12]. From a public management perspective, the ongoing use of PFCs with high global warming potential highlights a critical gap between current technological practices and the overarching goals of environmental stewardship in the industry. It underscores the need for robust regulatory frameworks that can guide and enforce sustainable practices. These frameworks must foster innovation in abatement technology and encourage the adoption of best practices throughout the industry's supply chain. Furthermore, regulations should be dynamic, capable of adapting to advancements in manufacturing technologies and the evolving scientific understanding of PFCs' environmental impacts [5].

3. Current Challenges in Managing PFC Emissions

3.1 Quantitative analysis of PFC Emissions and Their Impact on the Environment

Perfluorinated chemicals (PFCs) represent a class of compounds whose stability and persistence in the environment have raised global concerns. To effectively manage and supervise PFCs, rigorous quantitative analysis is essential. Modern techniques such as Gas Chromatography-Mass Spectrometry (GC-MS) and Liquid Chromatography-Mass Spectrometry (LC-MS) are employed to determine PFC concentrations in various mediums, offering insights into their pervasive nature. Ion chromatography and spectroscopic methods provide additional layers of analysis, with high sensitivity to fluorine ions and the ability to characterize chemical signatures, respectively. Scientific studies have linked PFCs to detrimental environmental effects, including bioaccumulation and toxicity in aquatic life, potential greenhouse gas effects, and persistence that leads to long-term environmental contamination [13]. Furthermore, data indicates that PFC emissions contribute to adverse health outcomes in humans, necessitating improved management from both policy and supply chain perspectives. The efficiency of PFC usage varies significantly across industries and specific processes. While the electronics and semiconductor industries demonstrate higher efficiency through recycling and reuse protocols due to the necessity for high-purity PFCs, other sectors like textiles and cosmetics exhibit considerable waste and low utilization efficiency. Often, these industries contribute to substantial wastewater and emissions, indicating a need for more sustainable practices and improved process management. For instance, while the semiconductor industry has adopted measures to minimize waste—such as recycling and reusing PFCs—the textile and cosmetics sectors present a different picture. In these sectors, PFCs are commonly used for their water and stain repellent properties, but the manufacturing process tends to be less efficient, often leading to significant PFC waste. The low concentration of PFCs in final products and the large volumes of wastewater and emissions during production contribute to this inefficiency. To address these issues, industries need robust supply chain management to ensure that PFCs are used more judiciously, combined with policies that encourage recycling and the development of sustainable alternatives. In light of recent environmental reports, there is also an increased call for industries to adopt circular economy principles, reducing the waste of PFCs through better design, reduced usage, and comprehensive recycling efforts. Such measures not only address environmental concerns but also present economic advantages by optimizing resource use and minimizing waste [13-14].

3.2 Challenges in Emission Abatement Due to the Diversity of Chemical Agents and Processes

The quest to manage perfluorinated chemical (PFC) emissions effectively is riddled with complexities, owing to the vast array of PFC compounds and their widespread application across diverse industries. In the aerospace sector, for example, PFCs are integral in crafting high-performance turbine engines, while in the medical field, they are essential in the production of life-saving devices such as artificial hearts and blood vessel stents. Similarly, their use in food packaging ensures the preservation and longevity of products. This multifaceted utilization presents a significant hurdle in standardizing emission abatement technologies. The challenge is not solely due to the range of applications but also the inherent chemical diversity of PFCs, which requires a bespoke approach to their management and containment [4]. Different industrial processes leverage the unique properties of PFCs to varying degrees, dictating tailored abatement strategies that align with the specific requirements of each application. To navigate this intricate landscape, emission abatement policies must be designed to be both adaptive and comprehensive, capable of accommodating the broad spectrum of PFC compounds and their respective industrial uses. Regulatory frameworks need to incorporate flexibility to cater to the evolving landscape of PFC applications while maintaining stringent controls to mitigate environmental and health impacts. An equally critical facet of addressing PFC emissions lies in the domain of supply chain management. A transparent and accountable supply chain ensures that the use of PFCs can be tracked, and sustainable practices can be systematically implemented and monitored. This requires a concerted effort to embed environmental accountability at every stage of the supply chain, from raw material extraction to final product disposal [5-6]. There is a pressing need

for policy initiatives that not only enforce regulations but also encourage the research and development of safer PFC alternatives. Incentives for innovation can catalyze the development of green chemistry solutions, fostering the creation of materials that emulate the beneficial properties of PFCs without their environmental drawbacks. Furthermore, enhancing recycling technologies and infrastructure can mitigate the impact of existing PFCs by diverting them from waste streams and reintroducing them into productive use. The interplay between policy, industry practice, and scientific innovation is therefore pivotal in overcoming the challenges posed by PFC emissions. It is through this synergy that progress towards a more sustainable and responsible use of these chemicals can be achieved, ensuring that the technological benefits of PFCs do not come at an untenable environmental cost [15].

4. Supply Chain Management Strategies

4.1 Analysis of the Semiconductor Supply Chain and the Integration of Environmental Practices

The semiconductor industry, valued at approximately \$481 billion in 2022, is anticipated to expand substantially in the coming years. This growth underscores the importance of sustainable practices in mitigating the environmental impact of perfluorinated compounds (PFCs), which are prevalent throughout the semiconductor supply chain.

- **Design Stage:** At the onset, design companies like Intel and Qualcomm play a critical role in shaping the environmental footprint of semiconductors. By implementing design for environment (DfE) principles, they can reduce the need for PFCs from the beginning. For example, Intel has managed to decrease its global warming potential by 30% by adopting PFC alternatives in its design protocols [16].
- **Manufacturing Stage:** Major manufacturers such as Samsung and TSMC are essential in minimizing PFC usage. Samsung, for instance, reported a 45% reduction in PFC emissions per production unit in 2021 by optimizing their manufacturing processes [17]. TSMC has similarly committed to reducing PFC emissions by 25% by utilizing recycling technologies in their chip fabrication processes.
- **Packaging and Testing Stage:** Packaging and testing companies, including Anwar High-tech and Renesas Electronics, are tasked with handling PFCs during the sensitive phase of chip completion. Recent industry reports suggest that improved capture and abatement systems can reduce PFC emissions by up to 85% during these stages [8].
- **Equipment Production Stage:** Equipment producers such as Applied Materials and ASML are positioned to make significant contributions to PFC reduction. Through innovations in machinery that utilize less PFCs, these companies can drastically alter the environmental landscape of semiconductor production. ASML has developed equipment that has shown to reduce PFC use by up to 50% during the lithography process.
- **Materials Production Stage:** Companies that supply semiconductor materials, like Tokyo Electronic Chemistry and Micron Technology, have a direct impact on PFC utilization. Efforts to replace PFCs with lower-impact materials have shown a potential decrease in associated emissions by up to 60%. Micron Technology, for instance, has invested in research to substitute traditional PFCs with advanced material formulations that promise a lower environmental burden.
- **Distribution Stage:** At the end of the supply chain, distributors like Arrow Electronics and Avnet have the power to influence industry practices by favoring products that adhere to environmental standards. They can leverage their position to advocate for products manufactured with reduced PFC emissions, creating market-driven demand for sustainable practices [9].

Across the supply chain, the integration of environmental practices is not just a matter of regulatory compliance but also a strategic differentiation factor. Companies that demonstrate commitment to reducing PFCs can benefit from increased market share and consumer trust, positioning themselves as leaders in the transition to a more sustainable future.

4.2 Strategies for Reducing PFC Usage in the Manufacturing Process, Including Technological Innovations and Process Optimization

The semiconductor manufacturing industry is a significant user of perfluorinated compounds (PFCs), with estimated global emissions attributed to the industry being approximately 15,000 metric tons annually. Addressing these emissions requires targeted strategies:

- **Process Optimization:** Studies have shown that semiconductor fabrication can reduce PFC usage by up to 90% through process optimization. Adjusting parameters such as reaction conditions and gas flows can enhance film quality and yield, thereby reducing PFC consumption. For instance, the implementation of gas flow modulators has been associated with a reduction of PFC usage by approximately 30% without affecting the quality of semiconductor layers.
- **Alternative Materials:** Transitioning to alternative materials such as silicon oxides or nitrides can lead to a substantial reduction in PFC reliance. Research indicates that alternatives like C₃F₈ can reduce the global warming potential by nearly 50% compared to conventional PFCs used in etching processes.
- **Waste Treatment:** Effective waste treatment and recycling can mitigate the environmental impact of PFCs. Enhanced plasma destruction technology for PFC waste treatment boasts destruction and removal efficiencies (DRE) exceeding 99.5%. These treatments, when paired with PFC recycling programs, can minimize the introduction of PFCs into the environment by reusing them in the manufacturing cycle.
- **Cleaner Production Technologies:** The introduction of cleaner production technologies, including advanced etching equipment that reduces PFC usage by up to 20%, is a testimony to technological innovation contributing to sustainability. In some facilities, improvements in chamber design and better precursor materials have led to a decrease in PFC emissions by approximately 10-15%, simultaneously reducing energy consumption by 5-10%.

By implementing these strategies, the semiconductor industry can align with the goals set by international agreements such as the Kyoto Protocol, which targets a global reduction of PFC emissions. As of the latest industry reports, these efforts have contributed to a decline in emissions intensity per semiconductor unit by about 30% over the past five years, signaling a positive trend towards sustainable manufacturing practices [18].

4.3 Role of Supply Chain Collaboration and Partnerships in Enhancing PFC Management Practices

Supply chain collaboration is pivotal in the semiconductor industry for the strategic management of PFCs. This multi-tiered approach has been quantitatively shown to improve environmental outcomes and operational efficiency:

- **Organizational Collaboration:** Reports indicate that when supply chain entities, from material suppliers to end-product distributors, collaborate on environmental initiatives, there can be a 10-15% improvement in PFC management. For example, a joint initiative by semiconductor companies resulted in a standardized method for calculating PFC emissions, leading to a 20% reduction in PFC emissions over three years.
- **Process-Level Collaboration:** The adoption of unified industry standards for PFC use, through organizations like the World Semiconductor Council, has led to the alignment of reduction goals across companies. Studies show that such alignment has the potential to cut industry-wide PFC emissions by up to 25% by optimizing processes and sharing best practices.

- **Informational Collaboration:** Digital integration across supply chains enables the sharing of real-time PFC usage data, significantly enhancing the ability to manage emissions. A recent survey showed that companies using integrated digital platforms for supply chain management saw a 30% increase in their ability to respond to PFC-related environmental incidents.
- **Partnerships for Innovation:** Collaborative partnerships, such as those between semiconductor manufacturers and environmental agencies, have facilitated the development of new PFC abatement technologies, e.g., the introduction of new abatement systems developed through such partnerships has led to a 40% improvement in the destruction efficiency of PFCs during semiconductor processing.
- **Economic Incentives and Policy Alignment:** Collaborative economic incentives for reducing PFC usage, such as tax benefits for environmentally-friendly manufacturing practices, have motivated companies throughout the supply chain. After the implementation of these incentives, some companies have reported up to a 50% increase in investment in PFC abatement and recycling technologies [11,19].

5. The Economic Impact of PFC Management

The economic implications of managing perfluorinated chemicals (PFCs) within the semiconductor industry are multifaceted and significant. From a cost-benefit perspective, the judicious application and management of PFCs can lead to a reduction in manufacturing expenditures. This economization is achieved through process optimization, the adoption of substitute materials, and the implementation of cleaner production technologies. These approaches not only curtail the direct costs associated with PFC procurement but also enhance production efficiency and elevate product quality, fostering further cost-effectiveness. Moreover, the strategic management of PFCs is increasingly becoming a determinant of brand prestige and competitive market positioning. In an era where environmental consciousness among consumers and corporations is escalating, the environmental stewardship of a company is a critical metric of its market appeal. By formulating and executing rigorous PFC management strategies, and strengthening environmental safety protocols, enterprises can significantly improve their brand image and competitive edge. Additionally, adept PFC management aligns with governmental incentives aimed at environmental conservation and sustainable industrial practices. Such alignment not only avails policy-driven fiscal advantages but also minimizes environmental liabilities [20]. This proactive engagement with PFC management mitigates potential economic and legal repercussions, thus shielding companies from the costs associated with non-compliance and environmental remediation. In the pursuit of cost-effective technological innovation within the semiconductor sector, a multifactorial analysis is indispensable. This comprehensive examination must encompass the nuances of technology development, market dynamics, the intricacies of cost structures, the spectrum of risks, and the projection of expected returns.

- **Technological Advancement and Innovation:** Advancements are contingent upon substantial investments in research and development (R&D), which necessitate the allocation of considerable financial resources to attract top-tier scientific talent, acquire state-of-the-art equipment, and ensure ongoing maintenance. High technical barriers, while fostering a competitive edge and potentially increasing market share, demand significant initial outlays and continuous investment to sustain innovation and stay ahead of the curve.
- **Market Demand Analysis:** A thorough analysis of market demand involves assessing the size and growth trajectory of the target market segments, such as emergent domains like 5G and AI chips, to gauge the investment's amortization period and potential profitability. Furthermore, discerning the heterogeneity in customer needs is essential to evaluate whether the new technology can satisfy a broad spectrum of customer requirements.
- **Cost Analysis:** The implementation of novel processes might alter the production cost matrix, influencing material expenses, energy utilization, and equipment depreciation rates. Additionally, the economies of scale could play a pivotal role, as certain new technologies

may witness a non-linear enhancement in return on investment concomitant with production upscaling [21].

- **Risk Assessment:** An appraisal of risks must account for the potential of technical setbacks, including unanticipated complications or the possibility of new technologies underperforming when applied practically. Market receptivity also constitutes a critical uncertainty factor, with variables such as technology adoption rates and consumer preferences [22].
- **Regulatory and Policy Environment:** Governmental policies, which may include fiscal incentives or subsidies, and compliance with environmental and safety regulations, are pivotal considerations that could significantly impact the feasibility and success of technological investments.
- **Financial Model and Return Forecast:** Financial modeling involves calculating the payback period to ascertain when the investment in new technology will break even. Additionally, forecasting the profit margins and cash flow variations post-implementation offers a lens through which to anticipate financial performance.

Investors and decision-makers in the semiconductor industry must employ a dynamic analytical approach to regularly update their assessments, aligning with the rapidly evolving technological landscape and market conditions. This iterative process aids in the discernment of the most advantageous investment opportunities, steering the semiconductor industry toward sustainable growth and innovation [23]. For semiconductor manufacturing enterprises, the integration of a sustainable development strategy is not merely a commitment to social responsibility and environmental stewardship but also a strategic move towards enhancing resource efficacy and long-term fiscal health. To facilitate the adoption of such strategies, governments and industry associations can deploy a suite of economic incentives: Tax incentives, such as deductions or credits, are potent tools that can be extended to corporations making strides in energy efficiency, waste minimization, and renewable energy deployment. Additionally, adjustments in import duties and value-added taxes for those utilizing eco-friendly technologies and materials can further encourage the shift towards sustainability. Financial subsidies and support also play a crucial role, offering direct investment for cleaner production technology adoption and upgrades to more sustainable operations, including the transition to energy-saving equipment and the development of environmentally conscious products and processes [24]. Credit support, in the form of low-interest loans and favorable lending conditions, can provide the necessary financial backing for businesses embarking on environmental enhancements and technological advancements. Market access advantages are another lever for change, with government procurement preferences and the establishment of green labels or certifications that can amplify market recognition and consumer confidence in sustainably produced goods. Research and development support is vital, channeling technical assistance and funds, particularly in domains aiming to cut energy use and emissions. Fostering collaborative ventures between industry players, academia, and research institutions can accelerate the innovation of advanced environmental technologies. Public-private partnerships (PPPs) can serve as conduits for collaborative efforts in technology development and implementation, fostering a cooperative approach to environmental projects. Such alliances, complemented by industry-wide knowledge sharing and technology transfer, can drive the sustainable evolution of the sector.

6. Conclusion

The management of perfluorinated compounds (PFCs) in semiconductor manufacturing presents a complex challenge that spans technological, regulatory, and economic domains. This paper has detailed the significant role that both supply chain strategies and public management policies play in addressing the environmental impacts of these high-GWP emissions. By integrating advanced abatement technologies, optimizing manufacturing processes, and enforcing robust regulatory frameworks, the industry can significantly reduce PFC emissions. The discussions herein highlight that proactive collaboration across industry stakeholders, including manufacturers, government bodies, and environmental agencies, is crucial. To achieve a sustainable balance, continuous

innovation in emission reduction technologies must be matched by equally dynamic regulatory policies that incentivize compliance and promote best practices. Moving forward, the semiconductor industry must continue to embrace its responsibility to innovate sustainably, ensuring that its growth does not come at the expense of the planet. The paper calls for a renewed commitment to environmental stewardship, guided by both enhanced technological practices and strengthened public management, to safeguard a future where technological advancements and environmental health are not mutually exclusive.

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Competing Interests

The authors declare no conflict of interest.

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