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Photochemical Smog and the Petroleum Industry: Sources, Mechanisms, Environmental Impacts, and Mitigation Strategies

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Abstract: This body of work synthesizes a comprehensive review of the multifaceted impacts of air pollution, with a specific focus on its sources, environmental and health consequences, and mitigation strategies. The included references span a range of topics, from industrial sources such as gas flaring and petroleum refining to the role of urban greenery and renewable energy in improving air quality. The compilation highlights the economic and health burdens of air pollution, as demonstrated by studies on fine particulate matter and tropospheric ozone, and reviews the effectiveness of control technologies like selective catalytic reduction. Additionally, the collection examines broader policy frameworks and energy transition pathways, including the role of carbon capture and storage (CCS) and the increasing adoption of electric vehicles (EVs), underscoring the interconnectedness of air quality, climate change, and sustainable development. The literature collectively points to a need for integrated solutions that address both the sources of pollution and their long-term effects on planetary and human health.

Keywords: *Air pollution, Environmental sustainability, Energy transition, Public health, Climate change*

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1.0 Introduction

Photochemical smog is a widespread atmospheric pollution problem that occurs when nitrogen oxides (NOx) and volatile organic compounds (VOCs) undergo complex photochemical reactions under the influence of sunlight, producing secondary pollutants such as ozone (O_3), peroxyacetyl nitrate (PAN), and secondary organic aerosols. First described in Los Angeles during the mid-twentieth century, photochemical smog has since become a global challenge in industrialized and urbanized areas. Its formation is closely associated with petroleum-related activities, ranging from crude oil exploration and refining to fuel combustion in transportation and power generation. The petroleum industry remains a dominant contributor of smog precursors, particularly in developing economies where regulatory enforcement and emission-control technologies are limited. Polymer degradation has also been found to be a secondary source of photochemical smog (Osabuohien, 2017; Osabuohien *et al*., 2023)

Numerous studies have highlighted the contribution of the petroleum industry to air pollution. For example, Finlayson-Pitts and Pitts (2020) provided a comprehensive discussion of atmospheric chemistry underlying smog formation, while Lee *et al*. (2022) reviewed the role of anthropogenic activities in tropospheric ozone formation. Case studies in megacities such as Los Angeles, Beijing, and New Delhi have demonstrated that emissions from petroleum combustion remain the primary drivers of smog episodes (Zhang *et al*., 2019; WHO, 2021). In Nigeria and other petroleum-rich nations, gas flaring, refinery emissions, and vehicle exhausts contribute substantially to ambient air pollution (Akinyemi *et al*., 2020). Although mitigation strategies such as catalytic converters, low-sulfur fuels, and renewable energy adoption have been widely reported, their implementation remains uneven across regions.

Despite the growing body of research, significant gaps remain. First, most existing studies focus on urban transport emissions, while the broader role of the petroleum industry—covering exploration, refining, storage, and distribution—receives less attention. Secondly, there is limited integration of data on the long-term health and ecological consequences of petroleum-derived smog in developing economies, where monitoring infrastructure is weak. Furthermore, while global mitigation strategies are widely discussed, region-specific approaches tailored to petroleum-dependent economies are underexplored. These gaps hinder the development of holistic solutions that balance energy needs with environmental sustainability.

This review aims to comprehensively examine the relationship between the petroleum industry and photochemical smog formation, with a focus on sources, mechanisms, environmental and health impacts, and mitigation strategies.

By synthesizing current knowledge and identifying knowledge gaps, this study provides a basis for policy design, technological innovation, and public health strategies targeted at reducing petroleum-related air pollution. The review is particularly significant for petroleum-dependent nations, where smog episodes undermine environmental integrity, human well-being, and economic sustainability. Ultimately, the findings contribute to advancing sustainable industrial practices and guiding the global transition toward cleaner energy alternatives.

2.0 Sources of Photochemical Smog from the Petroleum Industry

The petroleum industry is one of the most significant anthropogenic contributors to photochemical smog due to its emission of nitrogen oxides (NOx), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter at nearly every stage of production, refining, distribution, and consumption. The combination of these emissions with intense solar radiation, especially in tropical and subtropical regions, creates favorable conditions for smog formation (Finlayson-Pitts & Pitts, 2020; Lee *et al*., 2022).

To better conceptualize the multiple stages through which petroleum-related activities contribute to smog, Table 1 provides a synthesis of the principal emission sources, associated pollutants, and their potential impacts. Figure 1 presents a flowchart illustrating how emissions from petroleum-related processes interact with atmospheric chemistry to generate photochemical smog.

Table 1. Emission sources in the petroleum industry, associated pollutants, and their contributions to photochemical smog

Stage of Petroleum Industry	Major Activities	Key Pollutants Released	Contribution to Smog Formation
Exploration & Production	Gas flaring, drilling, crude storage	NOx, CO, VOCs, methane	Primary precursors of ozone; hydrocarbons amplify VOC burden in the troposphere.
Refining Processes	Catalytic cracking, distillation,	NOx, SO_2, BTX (benzene, toluene, xylene), aldehydes	Generation of aromatic hydrocarbons and NOx,

	petrochemical processing		enhancing photochemical oxidation cycles.
Transportation & End-Use Combustion	Automobiles, shipping, aviation	NOx, CO, unburned hydrocarbons, particulate matter	Dominant urban sources of smog precursors; sustained ozone production in high traffic areas.
Storage & Distribution	Tank farms, pipelines, filling stations	VOCs (especially evaporative emissions of gasoline)	Direct VOC emissions enhance ozone and PAN formation, particularly in warm climates.

Sources: Adapted from Akinyemi *et al*. (2020); Finlayson-Pitts & Pitts (2020); Lee *et al*. (2022); Zhang *et al*. (2019).

The table highlights that petroleum activities emit a broad range of pollutants, but NOx and VOCs are central to smog formation across all stages. Exploration and production, particularly gas flaring, release large volumes of NOx and VOCs, often in poorly regulated contexts. Refining processes introduce complex aromatic hydrocarbons that are especially reactive in forming secondary pollutants like peroxyacetyl nitrate (PAN). Transportation remains the most significant end-use contributor, particularly in megacities with high automobile density, where localized ozone concentrations are consistently elevated (WHO, 2021). Storage and distribution, though less visible, play a critical role in VOC leakage, which is particularly problematic in warmer climates that accelerate evaporation rates.

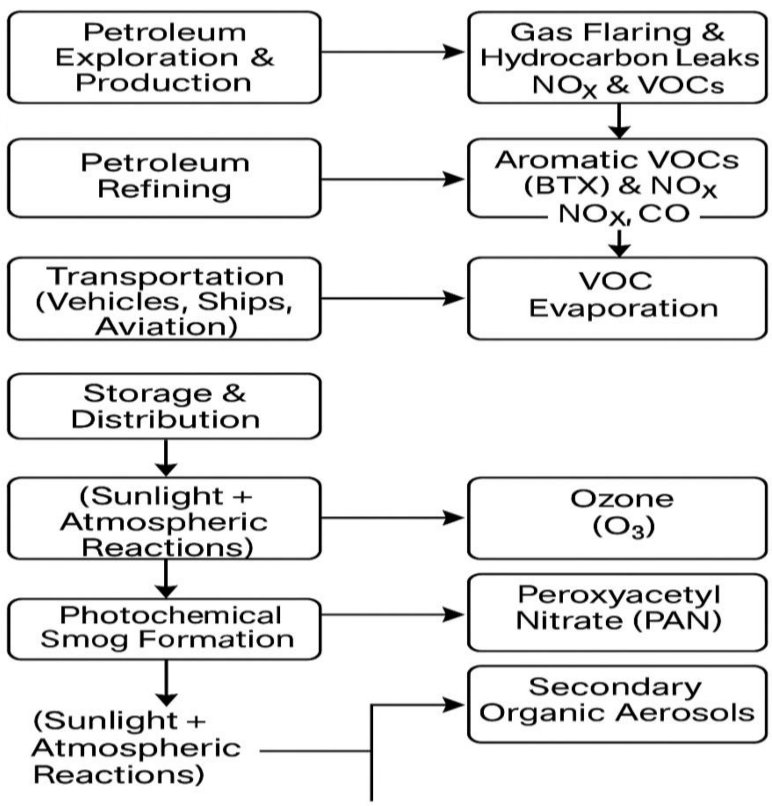

Fig. 1. Flowchart of petroleum industry contributions to photochemical smog

The flowchart demonstrates that emissions from petroleum industry activities converge into a common atmospheric pathway where sunlight triggers photochemical reactions. NOx and VOCs interact through free radical chemistry, leading to secondary pollutants such as ozone and PAN. The figure emphasizes that while emissions occur at multiple independent points—exploration, refining, transport, storage—their combined atmospheric chemistry leads to cumulative smog formation. This reinforces the idea that mitigating smog requires interventions across the petroleum value chain rather than focusing solely on end-use combustion.

3.0 Mechanisms of Photochemical Smog Formation

The formation of photochemical smog is a complex process involving primary emissions, solar radiation, and a cascade of atmospheric reactions that generate harmful secondary pollutants. Petroleum-derived activities release nitrogen oxides (NOx), volatile organic compounds (VOCs), carbon monoxide (CO), and particulate matter, which serve as key reactants in smog formation (Finlayson-Pitts & Pitts, 2020; Lee *et al*., 2022). The process occurs predominantly in urban areas with high traffic density and in petroleum-producing regions where gas flaring and refining activities are common.

3.1 Primary Pollutants

3.1.1 Nitrogen oxides (NO and NO_2)

Produced during high-temperature combustion of petroleum products in vehicle engines, refineries, and gas flaring operations. NO is oxidized in the atmosphere to NO_2, which plays a central role in initiating photochemical reactions.

3.1.2 Volatile Organic Compounds (VOCs)

Released from incomplete combustion of fossil fuels, evaporation of gasoline during storage and distribution, and emissions from petrochemical plants. VOCs include alkanes, alkenes, aldehydes, and aromatics such as benzene, toluene, and xylene (BTX). These compounds undergo oxidation in the presence of hydroxyl radicals (OH), forming peroxy radicals that drive the photochemical cycle.

3.2 Photochemical Reactions

The photochemical cycle begins when sunlight initiates the photolysis of nitrogen dioxide (NO_2):

3.2.1 Photolysis of NO_2

$NO2+hv(\lambda<430nm)\rightarrow NO+ONO_2 + hv\ (\lambda < 430\ nm) \rightarrow NO + ONO_2 +hv(\lambda<430nm)\rightarrow NO+O$

3.2.2 Ozone formation

$O+O_2+M\rightarrow O_3+MO + O_2 + M \rightarrow O_3 + MO+O_2 +M\rightarrow O3+M$

(where *M* represents a third body, typically N_2 or O_2, that stabilizes the reaction).

3.2.3 VOC oxidation

$VOC+OH\rightarrow RO2VOC + OH \rightarrow RO_2VOC+OH\rightarrow RO_2$

3.2.4 Radical propagation

$RO_2+NO\rightarrow NO_2+RORO_2 + NO \rightarrow NO_2 + RORO_2+NO\rightarrow NO_2+RO$

The newly formed NO_2 undergoes further photolysis, sustaining the cycle and leading to the continuous production of ozone (O_3) and other oxidants (Monks *et al*., 2015). Unlike stratospheric ozone, which protects against harmful ultraviolet radiation, tropospheric ozone is harmful to human health and ecosystems.

3.3 Secondary Pollutants

The interaction of primary pollutants through radical-driven photochemistry leads to the accumulation of several harmful secondary pollutants:

3.3.1 Ozone (O_3)

The most abundant oxidant in photochemical smog is responsible for respiratory irritation, lung inflammation, and reduced agricultural yields.

3.3.2 Peroxyacetyl nitrate (PAN)

Formed from aldehyde and NOx reactions. PAN is a strong lachrymator (eye irritant) and phytotoxic compound that damages plant tissues, reducing crop productivity.

3.3.3 Secondary Organic Aerosols (SOAs)

Generated when VOCs (such as terpenes, aromatics, and alkenes) undergo oxidation to produce low-volatility products that condense onto particles. SOAs contribute to haze, visibility reduction, and further oxidative stress in human lungs.

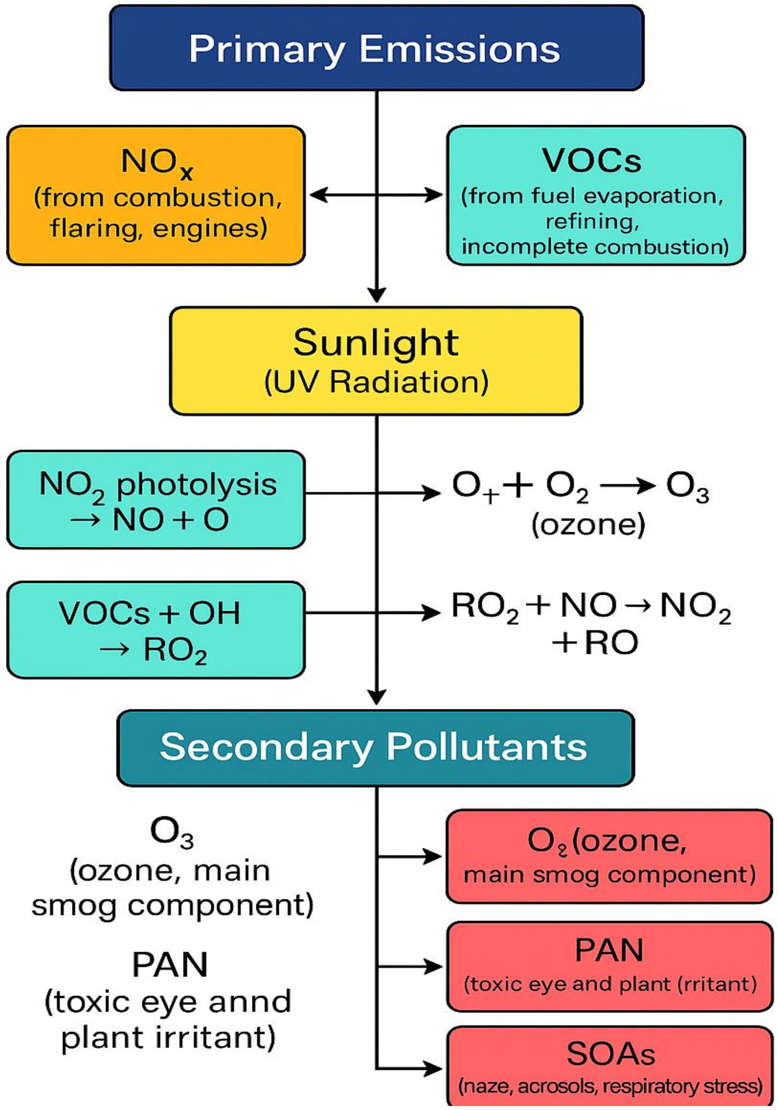

Fig. 2. Simplified Mechanism of Photochemical Smog Formation

Fig. 2 illustrates the self-sustaining nature of photochemical smog formation. Once initiated by sunlight, the cycle perpetuates through the continuous conversion of NO to NO_2 and back, with VOCs acting as catalysts that prevent NO from removing ozone. This explains why petroleum-dominated cities experience persistent ozone levels, especially during sunny seasons. Importantly, secondary pollutants such as PAN and SOAs add complexity to smog's environmental and health burden, making mitigation more challenging (Monks *et al*., 2015; WHO, 2021).

4.0 Environmental and Health Impacts

Photochemical smog is not only a localized urban pollution problem but also a global environmental and public health threat. It affects human well-being, ecosystems, agricultural productivity, and the durability of man-made structures. The combined health and environmental costs of smog often outweigh the economic benefits of petroleum-driven industrialization, particularly in heavily industrialized and petroleum-dependent economies (Lee *et al*., 2022; WHO, 2021).

4.1 Human Health

4.1.1 Respiratory Effects

Smog-related pollutants such as ozone (O_3), nitrogen dioxide (NO_2), and particulate matter cause significant respiratory complications. Ozone exposure induces airway inflammation, exacerbates asthma, and reduces lung function in both children and adults (Monks *et al*., 2015). Prolonged exposure increases the prevalence of chronic bronchitis and leads to diminished pulmonary capacity, especially in elderly populations.

4.1.2 Cardiovascular Effects

Oxidative stress induced by ozone and secondary organic aerosols (SOAs) contributes to systemic inflammation, which increases the risk of cardiovascular diseases. Epidemiological studies in Europe and Asia have demonstrated elevated hospital admissions for heart attacks, arrhythmias, and strokes during high-smog episodes (Pope *et al*., 2019).

Carcinogenic Risks

Certain VOCs released from petroleum refining, such as benzene and formaldehyde, are classified as Group 1 human carcinogens by the International Agency for Research on Cancer (IARC). Chronic exposure increases the risk of leukemia and other cancers (IARC, 2020).

4.1.3 Public Health Costs

The economic burden of smog is significant. Increased hospital admissions, premature mortality, and reduced workforce productivity collectively strain healthcare systems. The World Bank (2020) estimated that air pollution-related diseases cost the global economy trillions of dollars annually, with petroleum-heavy economies bearing a disproportionate burden.

4.2 Environmental Impacts

4.2.4 Agriculture

Tropospheric ozone is particularly damaging to crops such as wheat, rice, soybeans, and maize. Ozone enters plant leaves through stomata, leading to oxidative damage that reduces photosynthesis, growth, and ultimately yield. Studies have shown yield reductions of 10–20% in ozone-sensitive crops in smog-prone regions (Mills *et al*., 2018).

4.2.5 Forests and Biodiversity

Forests are also impacted, as ozone and PAN disrupt stomatal regulation in trees, reducing their carbon sequestration capacity and making them more vulnerable to drought and pests (Ainsworth *et al*., 2020). Long-term exposure to smog can reduce biodiversity, altering ecosystem balance.

Climate Interactions

Tropospheric ozone is a short-lived climate pollutant and the third most important anthropogenic greenhouse gas after CO_2 and methane. It contributes directly to radiative forcing and indirectly affects climate through feedback mechanisms that alter carbon and nitrogen cycles (IPCC, 2021). Petroleum-driven smog therefore exacerbates both local air quality problems and global warming.

4.3 Material Degradation

Photochemical smog accelerates the deterioration of building materials, cultural heritage, and infrastructure.

Corrosion and fading: Ozone, acidic aerosols, and oxidants cause cracking of rubber, fading of paints, and corrosion of metals.

Economic implications: Increased maintenance and repair costs are observed in smog-prone cities such as Los Angeles, Mexico City, and Beijing, where material degradation has become a significant urban management issue (Brimblecombe, 2019).

The impacts of photochemical smog underscore the urgent need for petroleum industries and governments to adopt effective emission control strategies. From a health perspective, reducing smog would lower the incidence of respiratory and cardiovascular diseases, improve workforce productivity, and reduce healthcare expenditure. From an environmental perspective, mitigation efforts would improve food security, enhance forest resilience, and reduce climate forcing. Additionally, protecting infrastructure from premature degradation contributes to urban sustainability and reduces economic losses.

5.0 Mitigation Strategies

The complexity of photochemical smog formation requires multi-layered interventions, ranging from regulatory frameworks and advanced technologies to systemic transitions toward sustainable energy. Because petroleum activities are central to smog generation, mitigation strategies must address emissions across exploration, refining, transport, storage, and end-use combustion. Integrated approaches combining regulation, technology, sustainability, and public awareness are essential for lasting impact (Lee *et al*., 2022; Ekins *et al*., 2023).

5.1 Regulatory Approaches

5.1.1 Emission Standards

Stricter emission standards for petroleum refineries and vehicles represent the foundation of smog control. For instance, the Euro 6 vehicle emission standards have significantly reduced NOx and particulate matter emissions across Europe (European Environment Agency, 2020). Petroleum refineries are increasingly required to use desulfurization and NOx reduction units to meet international benchmarks.

5.1.2 Air Quality Monitoring

Real-time monitoring networks, supported by satellite data and ground-based stations, are critical in tracking NOx, VOCs, and ozone concentrations. China's nationwide monitoring system, established since 2013, has been instrumental in identifying pollution hotspots and enforcing targeted interventions (Zhang *et al*., 2019).

5.1.3 Cap-and-Trade Policies

Market-based mechanisms such as emission trading schemes incentivize industries to reduce pollutants at lower costs. The U.S. Acid Rain Program and the EU Emissions Trading Scheme (ETS) have demonstrated the effectiveness of cap-and-trade systems in reducing SO_2 and NOx emissions, which are also precursors to ozone (Tietenberg, 2018).

5.2 Technological Solutions

5.2.2 Cleaner Fuels

The transition to low-sulfur fuels, compressed natural gas (CNG), liquefied natural gas (LNG), and biofuels reduces the sulfur and aromatic content of emissions, thereby lowering ozone precursor formation. Ultra-low-sulfur diesel (ULSD) has already been shown to reduce NOx and VOC emissions significantly (USEPA, 2020).

5.2.3 Emission Control Devices

Catalytic converters for vehicles oxidize CO and hydrocarbons into less harmful CO_2 and H_2O while reducing NOx to N_2. In refineries, selective catalytic reduction (SCR) systems lower NOx emissions by injecting ammonia or urea into exhaust streams (Chen *et al*., 2019).

5.2.4 Vapor Recovery Systems

Stage I and Stage II vapor recovery systems minimize VOC losses from storage tanks and fuel dispensing stations, especially in hot climates where evaporation is intensified (Akinyemi *et al*., 2020).

5.2.5 Carbon Capture and Utilization (CCU)

Although primarily aimed at CO_2 reduction, carbon capture and utilization technologies in refineries and power plants indirectly reduce smog precursors by decreasing fossil fuel combustion and optimizing process efficiency (Bui *et al*., 2018).

5.3 Sustainable Alternatives

5.3.1 Renewable Energy Integration

Solar, wind, and hydrogen are increasingly viable substitutes for petroleum-based energy. Their integration into national grids not only reduces NOx and VOC emissions but also diversifies energy sources to enhance sustainability (IRENA, 2022).

5.3.2 Electrification of Transport

Electric vehicles (EVs), powered by renewable energy, eliminate tailpipe emissions of NOx and VOCs, offering a direct pathway to smog reduction. Countries such as Norway, where EV adoption is high, have reported improved air quality in urban centers (IEA, 2021).

5.3.3 Green Refinery Technologies

Modern refineries are adopting closed-loop systems that recycle wastewater, recover waste heat, and minimize flaring. These innovations reduce direct emissions and contribute to sustainable industrial development (Ghosh *et al*., 2020).

5.4 Public Awareness and Urban Planning

5.4.1 Promotion of Public Transportation and Carpooling

Expanding affordable and efficient public transportation systems reduces vehicle density, thereby lowering smog precursors. Carpooling initiatives in megacities such as Lagos, Los Angeles, and Beijing have been shown to reduce traffic-related smog (WHO, 2021).

5.4.2 Tree Planting and Green Belts

Urban greenery absorbs ozone and NO_2 while acting as physical barriers to pollutant dispersion. Green belts around petroleum refineries and industrial zones reduce local smog intensity and improve air quality (Nowak *et al*., 2018).

5.4.3 Public Health Campaigns

Awareness campaigns help vulnerable populations (e.g., children, elderly, asthmatics) mitigate exposure during smog episodes. Public advisories in California, for instance, recommend limiting outdoor activities during high-ozone days (California Air Resources Board, 2020).

Effective mitigation of photochemical smog requires a systems approach that integrates upstream (exploration and refining), midstream (transportation and distribution), and downstream (consumption) solutions. While regulatory enforcement sets a foundation, technological innovation provides immediate pollution reduction. Long-term sustainability depends on energy transitions and changes in public behavior. Importantly, strategies must be **context-specific**: developed nations can prioritize electrification and CCU, while petroleum-dependent developing countries may need phased approaches combining regulation, technology transfer, and renewable investments.

6.0 Future Directions

Future research on photochemical smog and its relationship with the petroleum industry must focus on advancing scientific, technological, and policy dimensions. One critical area is the development of advanced photochemical models that can predict smog formation under varying industrial emission scenarios. Current models provide valuable insights but often fail to capture the complexity of interactions between NOx, VOCs, meteorology, and local emission inventories, particularly in petroleum-dependent economies where monitoring data are scarce. Improved models integrating atmospheric chemistry, satellite observations, and machine learning could enhance forecasting accuracy and guide effective interventions.

Equally important is innovation in petroleum refining technologies aimed at achieving near-zero emissions. Conventional refining processes, such as catalytic cracking and hydrodesulfurization, continue to release substantial amounts of NOx, SO_2, and VOCs. Emerging technologies, including green refinery concepts, advanced carbon capture, and closed-loop systems, have the potential to minimize emissions across the petroleum value chain. Research that optimizes these technologies for large-scale application, especially in developing countries, will be vital for global air quality improvement.

Another future direction involves promoting interdisciplinary studies that link petroleum economics, climate change, and air quality. Most existing research tends to treat these areas in isolation. However, petroleum economics influence production intensity, which in turn affects emission levels, while climate variability modifies pollutant dispersion and photochemical reaction rates. Integrated research frameworks that combine atmospheric science, economics, and environmental policy can better inform decisions that balance energy security with environmental sustainability.

Finally, stronger collaboration between petroleum industries, regulators, and local communities is essential for long-term solutions. In many petroleum-producing regions, weak enforcement of emission standards and limited public participation hinder effective mitigation. Partnerships that encourage transparency, stakeholder engagement, and shared responsibility can foster sustainable practices and ensure that technological innovations are supported by regulatory compliance and public acceptance. Such collaborations could also provide valuable community-based data to supplement scientific monitoring and strengthen adaptive capacity in smog-prone regions.

In summary, the future of smog mitigation in the petroleum sector depends on scientific innovation, sustainable industrial transformation, interdisciplinary integration, and robust multi-stakeholder cooperation. Addressing these research needs will provide a pathway toward cleaner air, healthier populations, and a more sustainable energy future.

7.0 Conclusion

This review has examined the role of the petroleum industry in the formation of photochemical smog, highlighting the sources, mechanisms, impacts, and potential mitigation strategies. The findings show that petroleum-related activities such as gas flaring, refining, transportation, and fuel storage are major sources of nitrogen oxides and volatile organic compounds, which act as primary precursors of smog. The interaction of these pollutants under sunlight initiates photochemical reactions that generate secondary pollutants including ozone, peroxyacetyl nitrate, and secondary organic aerosols. The review also revealed that smog poses significant threats to human health by increasing the risk of respiratory illnesses, cardiovascular diseases, and certain cancers, while simultaneously undermining agricultural productivity, forest health, climate stability, and the durability of infrastructure.

The conclusion drawn from this study is that photochemical smog remains a pressing global environmental challenge that is intricately linked with petroleum industry operations across the entire value chain. Its impacts are multidimensional, affecting not only public health but also ecosystems, agricultural output, climate change, and economic sustainability. The persistence of smog in petroleum-dependent economies underscores the need for urgent, coordinated, and systemic approaches to mitigation.

Based on these insights, the study recommends the adoption of stronger regulatory frameworks, including stricter emission standards for refineries and vehicles and enhanced air quality monitoring systems to track pollutants in real time. Technological solutions such as catalytic converters, selective catalytic reduction systems, vapor recovery technologies, and carbon capture should be widely implemented in petroleum industries, while cleaner fuels and renewable energy sources should gradually replace conventional fossil fuels. Transitioning toward sustainable alternatives such as electric vehicles and green refinery technologies will further reduce smog precursors. In addition, public awareness, urban planning initiatives, and community engagement must be prioritized to complement industrial and regulatory interventions. Future efforts should emphasize interdisciplinary research, innovation in refining technologies, and stronger collaboration among petroleum industries, regulators, and local communities. Collectively, these measures will help reduce the burden of photochemical smog, safeguard human and environmental health, and promote a sustainable pathway for energy and industrial development.

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There are no known financial competing interests to disclose

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Authors' Contributions

All components of the work were carried out by the two authors together