



Understanding Vehicle Air Pollution through Haagen-Smit's Photochemical Smog Theory: An Integrative Literature Review for Environmental Science Education

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ABSTRACT

Vehicle-related air pollution is widely discussed as an environmental and public health problem, yet its pedagogical potential for environmental science education remains underdeveloped. This article examines how Haagen-Smit's photochemical smog theory can serve as a conceptual bridge between atmospheric chemistry and socio-scientific issue-based learning. This study employs an integrative literature review approach by synthesizing historical scientific literature, peer-reviewed studies, academic books, and institutional reports on vehicle emissions, nitrogen oxides, volatile organic compounds, ground-level ozone, mitigation strategies, scientific literacy, and environmental science education. The review shows that vehicle-related air pollution originates from fossil fuel combustion and secondary atmospheric reactions in which nitrogen oxides and volatile organic compounds interact under sunlight to form photochemical smog and ground-level ozone. Haagen-Smit's work remains pedagogically significant because it explains how invisible chemical reactions produce observable environmental problems and inform public policy. The synthesis further indicates that mitigation should be taught as an integrated socio-scientific problem involving clean energy, electric mobility, public transportation, urban planning, regulation, and behavioral change. This article contributes by positioning vehicle-related air pollution as a contextual learning issue that supports environmental chemistry understanding, evidence-based reasoning, policy evaluation, and responsible citizenship.

Keywords: Vehicle Emissions; Photochemical Smog; Haagen-Smit; Integrative Literature Review; Environmental Science Education; Scientific Literacy

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INTRODUCTION

Vehicle-related air pollution represents a persistent environmental science problem because it connects fossil fuel combustion, atmospheric chemical reactions, public health risks, transportation systems, and everyday human behavior. Globally, ambient outdoor air pollution was estimated to cause approximately 4.2 million premature deaths in 2019, largely through exposure to fine particulate matter associated with cardiovascular and respiratory diseases (WHO, 2024). The transport sector also remains significant in environmental degradation, with the IPCC reporting that direct transport emissions accounted for 23% of global energy-related CO₂ emissions in 2019, and that road vehicles contributed about 70% of direct transport emissions (IPCC, 2022). Cars, motorcycles, buses, and trucks emit complex mixtures of pollutants, including nitrogen oxides, carbon monoxide, volatile organic compounds, particulate matter, and other substances that can harm the atmosphere and human health either directly or through secondary chemical reactions (Bai et al., 2022; Ravi et al., 2023; WHO, 2021).

However, the scientific and pedagogical significance of vehicle-related air pollution is often treated separately. In environmental science and public health literature, vehicle emissions are commonly discussed in relation to pollutant exposure, disease burden, and mitigation policy. In science education, environmental issues are frequently used to promote awareness and responsibility, but the underlying atmospheric chemistry and historical development of scientific explanations are not always made explicit. This creates an important research tension: vehicle-related air pollution is scientifically complex and socially relevant, yet its potential as a contextual learning issue for connecting chemistry, evidence-based reasoning, environmental policy, and responsible citizenship remains insufficiently synthesized.

Vehicle-related air pollution is pedagogically important because it allows environmental science education to move beyond general awareness of pollution toward evidence-based explanation and decision-making. Unlike some environmental issues that are taught primarily as moral or conservation messages, vehicle-related air pollution requires students to connect observable daily experiences, such as traffic congestion and vehicle exhaust, with less visible scientific mechanisms, including fossil fuel combustion, nitrogen oxide emissions, volatile organic compounds, photochemical reactions, and ground-level ozone formation. This makes the topic suitable for socio-scientific issue-based learning because students must interpret scientific evidence, evaluate technological and policy responses, and consider the consequences of individual and collective mobility choices (Sadler, 2004; Zeidler et al., 2019).

The health dimension of vehicle-related air pollution also has direct educational relevance. Public health evidence shows that exposure to fine particulate matter, nitrogen dioxide, and ground-level ozone is associated with respiratory and cardiovascular risks, particularly in areas near roads, schools, workplaces, and residential zones (Bai et al., 2022; Cohen et al., 2017; HEI, 2022; WHO, 2021, 2024). In environmental science learning, this evidence can be used not merely to show that air pollution is harmful, but to help students reason about pollutant exposure, vulnerable populations, risk reduction, and the social consequences of transportation systems. Therefore, the health impacts of air pollution function as a bridge between atmospheric chemistry and environmental citizenship, enabling students to understand why scientific explanations matter for public decision-making.

A scientific explanation of vehicle-related smog is closely associated with Arie Haagen-Smit's research on Los Angeles smog. Haagen-Smit (1952) demonstrated that hydrocarbons and nitrogen oxides released into the atmosphere could react under sunlight to form ozone and other oxidants. This finding became central to the modern understanding of photochemical smog. It also revealed that visible environmental problems may be driven by invisible atmospheric reactions, and that scientific evidence can shape public policy, emission standards, and technological innovation.

Haagen-Smit's contribution remains relevant because photochemical smog continues to affect many urban areas. However, contemporary vehicle-related air pollution is more complex than the smog problem observed in mid-twentieth-century Los Angeles. Modern transportation systems involve increasing numbers of private vehicles, high energy demand, urban expansion, industrial activity, and climate-related emissions. Although catalytic converters, emission standards, cleaner fuels, and electric vehicles have reduced certain pollutants, vehicle-related air pollution cannot be addressed through vehicle technology alone. Emission reduction also requires cleaner energy systems, transport reform, sustainable urban planning, stronger regulation, and changes in mobility behavior (IEA, 2023; IPCC, 2023; Ravi et al., 2023).

This complexity has important implications for environmental science education. If vehicle-related air pollution is taught only as a technical problem of exhaust control, students may overlook the broader scientific and social systems that shape pollution. They need to understand not only how combustion releases pollutants, but also how urban design, energy sources, transport choices, regulation, and public behavior influence air quality. Therefore, Haagen-Smit's photochemical smog theory can be used as an entry point for teaching vehicle-related air pollution as a socio-scientific issue that connects atmospheric chemistry, technological change, environmental governance, and responsible citizenship.

Scientific literacy is central to this educational challenge. OECD (2023) defines scientific literacy as the capacity to explain phenomena scientifically, evaluate evidence, and apply scientific knowledge in decision-making. Sadler (2004) and Zeidler et al. (2019) further emphasize that socio-scientific issue-based learning can connect scientific content with real-world problems involving values, uncertainty, policy, and social consequences. Air pollution is particularly suitable for this approach because learners must examine evidence, understand scientific mechanisms, evaluate possible solutions, and reflect on the consequences of human behavior.

Recent studies in science education have shown that contextual, STEM-based, and socio-scientific issue-based learning can strengthen scientific literacy, critical thinking, and students' ability to connect science with real-world problems (Mabsutsah & Yushardi, 2022; Muttaqin, 2023; Rohmaya, 2022; Wisdayana et al., 2025; Zandroto & Sinaga, 2022). However, much of this literature discusses environmental issues as broad learning contexts rather than as scientifically specific problems grounded in atmospheric chemistry. Local studies tend to

emphasize the development of teaching materials, contextual learning, or literacy improvement, while international socio-scientific issue literature provides a broader theoretical basis for reasoning, decision-making, and citizenship-oriented science education (Sadler, 2004; Zeidler et al., 2019). What remains limited is an integrative synthesis that connects vehicle-related air pollution, Haagen-Smit's photochemical smog theory, contemporary mitigation strategies, and their pedagogical relevance for environmental science education. This limitation is important because students may develop environmental awareness without fully understanding the chemical mechanisms and policy implications behind vehicle-related air pollution.

Despite the extensive literature on air pollution, vehicle emissions, and science education, several conceptual gaps remain. Environmental science studies have widely discussed vehicle emissions, ozone formation, traffic-related air pollution, and health impacts. At the same time, science education studies have examined scientific literacy, contextual learning, and socio-scientific issue-based instruction. However, limited attention has been given to integrating Haagen-Smit's photochemical smog theory with contemporary vehicle pollution challenges and its pedagogical relevance for environmental science education. This gap is important because Haagen-Smit's work can serve not only as a historical scientific explanation of smog formation, but also as a conceptual bridge between atmospheric chemistry, environmental policy, and responsible citizenship.

In science education, such integration is necessary because environmental issues are often taught either as general moral messages or as isolated scientific concepts. When air pollution is presented only as a problem of dirty air, students may not fully understand the chemical mechanisms that produce secondary pollutants such as ground-level ozone. Conversely, when photochemical reactions are taught only as abstract chemistry, students may not recognize their relevance to public health, transportation policy, energy transition, and daily mobility choices. Therefore, vehicle-related air pollution provides a meaningful context for connecting scientific concepts with socio-scientific reasoning and environmental decision-making.

Based on this gap, this article aims to: (1) examine the scientific causes of vehicle-related air pollution, particularly fossil fuel combustion and atmospheric reactions involving nitrogen oxides and volatile organic compounds; (2) explain Arie Haagen-Smit's contribution to the understanding of photochemical smog; and (3) synthesize contemporary strategies for reducing vehicle-related air pollution in the context of environmental science education. By integrating literature from atmospheric chemistry, public health, environmental policy, energy transition, and science education, this article offers a conceptual framework for using vehicle-related air pollution as a socio-scientific issue to strengthen scientific literacy and environmental responsibility.

The contribution of this article is theoretical and pedagogical. Theoretically, this article clarifies the continuing relevance of Haagen-Smit's photochemical smog theory for understanding vehicle-related air pollution. It shows that the theory remains useful not only as a historical explanation of Los Angeles smog, but also as a conceptual foundation for explaining the relationship between vehicle emissions, atmospheric reactions, and secondary pollutant formation.

Pedagogically, this article positions vehicle-related air pollution as a contextual learning issue for environmental science education. It shows how the topic can connect chemistry, environmental science, public health, technology, policy discussion, and environmental citizenship. Practically, the article also identifies integrated mitigation strategies, including clean energy, electric mobility, public transportation, sustainable urban planning, regulation, and behavioral change, that can be discussed in science learning to strengthen students' scientific literacy and socio-scientific reasoning.

To address these aims, this study employs an integrative literature review approach that enables conceptual synthesis across atmospheric chemistry, public health, environmental policy, transportation studies, and environmental science education.

METHODS

Research Design and Rationale

This study employed an integrative literature review design to synthesize existing knowledge on vehicle-related air pollution, Haagen-Smit's photochemical smog theory, and contemporary mitigation strategies in the context of environmental science education. An integrative review was selected because the purpose of this article was not to conduct a meta-analysis or a fully systematic review of intervention effects, but to develop a conceptual

synthesis across multiple bodies of literature, including atmospheric chemistry, public health, environmental policy, transportation studies, and science education. This approach is appropriate for examining complex multidisciplinary issues because it allows empirical studies, theoretical publications, historical scientific work, and institutional reports to be integrated into a coherent interpretive framework (Cooper, 1988; Snyder, 2019; Torraco, 2005).

Review Questions

The review was guided by three analytical questions. First, how can the scientific mechanisms of vehicle-related air pollution, particularly fossil fuel combustion, nitrogen oxide emissions, volatile organic compounds, particulate matter, and ozone formation, be synthesized to support environmental science learning? Second, how can Haagen-Smit's photochemical smog theory be reconstructed as a conceptual bridge between atmospheric chemistry, environmental policy, and public understanding of air pollution? Third, how can contemporary mitigation strategies for vehicle-related air pollution be evaluated as socio-scientific learning contexts for strengthening scientific literacy and environmental citizenship?

Search Strategy and Sources

The literature search was conducted through Google Scholar, ScienceDirect, SpringerLink, PubMed, and official websites of relevant international institutions. Institutional sources were included when they were published by recognized organizations such as the World Health Organization, International Energy Agency, Intergovernmental Panel on Climate Change, European Environment Agency, and Health Effects Institute. The search focused primarily on publications from 2014 to 2025 to capture contemporary discussions on vehicle emissions, mitigation strategies, public health relevance, and environmental science education. Older sources were retained when they had foundational relevance, particularly Haagen-Smit's original work on photochemical smog and classic literature on ozone formation and literature review methodology.

The search used combinations of keywords such as "vehicle-related air pollution," "vehicle emissions," "photochemical smog," "Haagen-Smit," "nitrogen oxides," "volatile organic compounds," "ground-level ozone," "particulate matter," "electric vehicles," "air pollution mitigation," "transport emissions," "environmental science education," "scientific literacy," and "socio-scientific issues." The term "vehicle-related air pollution" was used as the main term throughout this review, while "traffic-related air pollution" was retained only when referring to specific public health literature that uses this term.

Inclusion and Exclusion Criteria

Sources were included when they directly addressed at least one of the main analytical areas of this review: vehicle emissions, fossil fuel combustion, photochemical smog, ozone formation, nitrogen oxides, volatile organic compounds, particulate matter, traffic-related exposure, health impacts of air pollution, emission regulation, clean energy transition, transportation policy, scientific literacy, socio-scientific issue-based learning, or environmental science education. Peer-reviewed journal articles, academic books, historical scientific publications, and institutional reports from credible organizations were considered eligible.

Sources were excluded when they discussed air pollution only in general terms without a clear connection to vehicle emissions, atmospheric chemistry, mitigation strategies, health impacts, or educational relevance. Non-academic materials were also excluded when they lacked clear authorship, institutional credibility, verifiable publication information, or relevance to the analytical focus of this review. Sources with highly overlapping content were not prioritized unless they offered distinct empirical, theoretical, historical, or pedagogical contributions.

Screening and Selection Process

The literature selection was conducted through an iterative screening process consistent with the purpose of an integrative literature review. The review did not aim to conduct a full systematic review or meta-analysis, but to develop a conceptual synthesis of representative literature across atmospheric chemistry, public health, environmental policy, transportation studies, and environmental science education. Therefore, the selection process emphasized relevance, credibility, recency, and conceptual contribution to the review questions.

Search results were first screened by title and abstract to identify sources related to vehicle-related air pollution, photochemical smog, Haagen-Smit's contribution, mitigation strategies, public health relevance,

scientific literacy, and environmental science education. Sources that were too general, duplicated in topic coverage, or not directly connected to the analytical focus of the study were excluded. Potentially relevant sources were then examined through full-text reading. During this stage, each source was assessed based on its relevance to the review questions, credibility of publication, methodological clarity, and contribution to the conceptual synthesis.

The final synthesis included 24 sources, consisting of peer-reviewed journal articles, historical scientific literature, academic references on literature review methodology, and institutional reports from credible organizations. These stages were applied to ensure transparency in the selection process and to confirm that the selected sources were relevant, credible, and appropriate for integrative conceptual synthesis.

To clarify the transparency of the literature selection process, the stages of source identification, title and abstract screening, duplicate and overlap checking, full-text eligibility review, and final synthesis are summarized in Table 1. This summary explains how the literature was narrowed based on relevance, credibility, recency, methodological clarity, and conceptual contribution to the aims of the integrative review.

Table 1. Summary of Literature Selection Process

Stage	Selection activity	Result
Identification	Literature was searched through academic databases and institutional websites using keywords related to vehicle-related air pollution, photochemical smog, Haagen-Smit, mitigation strategies, scientific literacy, and environmental science education.	Search results were screened iteratively
Title and abstract screening	Sources were assessed for relevance to vehicle-related air pollution, atmospheric chemistry, mitigation, public health, and science education.	Irrelevant and overly general sources were excluded
Duplicate and overlap checking	Sources with duplicate records or highly overlapping topic coverage were removed or deprioritized.	Duplicate and redundant sources were excluded
Full-text eligibility review	Potentially relevant sources were examined based on credibility, recency, methodological clarity, and conceptual contribution.	Eligible sources were retained
Final synthesis	Sources were thematically analyzed for integrative conceptual synthesis.	24 sources included

Quality Appraisal of Sources

The quality and credibility of the selected literature were assessed using several criteria. Peer-reviewed studies were evaluated based on their relevance to the review questions, clarity of research focus, methodological transparency, and contribution to the conceptual synthesis. Institutional reports were evaluated based on the credibility of the publishing organization, transparency of data sources, publication recency, and relevance to vehicle-related air pollution, environmental policy, transport emissions, or public health. Historical and foundational sources were retained when they made a significant conceptual contribution to understanding photochemical smog, ozone formation, or literature review methodology.

To strengthen the trustworthiness of the review, source triangulation was applied by comparing evidence across historical scientific literature, contemporary atmospheric chemistry studies, public health research, institutional reports, transportation policy literature, and science education studies. This triangulation helped reduce dependence on a single type of source and supported a more balanced interpretation of the scientific, policy, and educational dimensions of vehicle-related air pollution.

Data Analysis and Thematic Synthesis

The selected sources were analyzed through thematic synthesis. The analysis was conducted in four stages. First, the sources were read repeatedly to identify recurring concepts, arguments, findings, and conceptual relationships. Second, relevant information was coded into analytical categories, including fossil fuel combustion, nitrogen oxides, volatile organic compounds, ozone formation, particulate matter, health impacts, emission standards, catalytic converters, electric vehicles, renewable energy, public transportation, urban planning, behavioral change, scientific literacy, and socio-scientific issue-based learning. Third, related codes were grouped into broader themes. Fourth, the themes were interpreted in relation to the review questions and their relevance to environmental science education.

The synthesis generated four major themes: fossil fuel combustion as a major source of vehicle-related air pollution; photochemical smog formation through the interaction of nitrogen oxides, volatile organic compounds, and sunlight; Haagen-Smit's contribution to the scientific and policy understanding of smog formation; and contemporary mitigation strategies involving clean energy, transportation reform, regulation, behavioral change, and environmental education. These themes provided the basis for constructing the conceptual discussion of vehicle-related air pollution as a socio-scientific issue in environmental science education.

RESULTS AND DISCUSSION

The synthesis identifies four interrelated themes. First, vehicle-related air pollution is closely linked to fossil fuel combustion, particularly from gasoline- and diesel-powered transportation. Second, photochemical smog forms through atmospheric reactions involving nitrogen oxides, volatile organic compounds, and sunlight. Third, Arie Haagen-Smit's contribution remains significant because his work clarified the chemical mechanism of smog formation and helped shape emission-control policies. Fourth, contemporary air pollution reduction requires integrated strategies involving clean energy, electric mobility, public transportation, urban planning, regulatory enforcement, and environmental science education. Taken together, these themes show that vehicle-related air pollution should be understood not only as an atmospheric chemistry issue, but also as a socio-technical and educational problem.

Fossil Fuel Combustion as the Scientific Root of Vehicle-Related Air Pollution

The literature consistently identifies fossil fuel combustion as a major source of vehicle-related air pollution. Gasoline and diesel engines release various pollutants into the atmosphere, including nitrogen oxides, carbon monoxide, volatile organic compounds, and particulate matter. These pollutants are produced when hydrocarbon fuels are burned to generate energy for transportation. Although combustion supports modern mobility, it also generates emissions that affect air quality, human health, and ecological systems (Bai et al., 2022; Ravi et al., 2023).

Vehicle pollution should therefore not be understood only as visible exhaust smoke. Its scientific basis lies in the chemical process of burning fossil fuels and releasing primary pollutants into the atmosphere. Some pollutants, such as carbon monoxide and particulate matter, can directly harm human health. Others, such as nitrogen oxides and volatile organic compounds, act as precursors that form secondary pollutants through atmospheric reactions. Ground-level ozone, for example, is not emitted directly in large quantities from vehicles, but is formed when precursor gases interact with sunlight and other atmospheric conditions (Haagen-Smit, 1952; Sillman, 1999).

The distinction between primary and secondary pollutants is important for science education. In everyday observation, air pollution is often associated with black smoke, unpleasant odor, or visible haze. However, some of the most harmful pollutants are invisible or are formed only after emissions enter the atmosphere. Students therefore need more than observational awareness. They need conceptual understanding of combustion, chemical reactions, atmospheric transformation, and pollutant exposure. Vehicle-related air pollution provides a meaningful context for teaching environmental chemistry and scientific literacy.

The synthesis also shows that vehicle-related air pollution is connected to broader energy dependence. Transportation systems in many countries still rely heavily on oil-based fuels. This dependence makes air pollution difficult to address through individual behavior alone. Even when people are aware of pollution, they may continue using private vehicles because public transportation is limited, urban planning is car-oriented, or cleaner alternatives remain expensive. Fossil fuel combustion is therefore both a chemical cause and a structural problem embedded in modern transportation systems. Cleaner vehicle technologies can reduce emissions, but broader energy transition is needed to address the underlying dependence on fossil fuels (IEA, 2023; IPCC, 2023).

From an educational perspective, this theme suggests that environmental science learning should connect chemistry with energy systems. Students need to understand that vehicles do not produce pollution simply because they move, but because their movement is powered by fuel combustion. This understanding can help learners relate air pollution to broader topics such as energy transition, renewable energy, climate change, and sustainable transportation. Such integration is consistent with socio-scientific issue-based learning because it

encourages students to connect scientific explanation with real-world environmental decision-making (Sadler, 2004; Zeidler et al., 2019).

Photochemical Smog Formation through NO_x, VOCs, and Sunlight

The second major theme concerns the formation of photochemical smog through reactions between nitrogen oxides, volatile organic compounds, and sunlight. This theme is central to Haagen-Smit's contribution to atmospheric chemistry. Haagen-Smit (1952) demonstrated that smog in Los Angeles was not caused only by factories, smoke, or waste burning, but by chemical reactions involving vehicle exhaust gases under sunlight. His work showed that hydrocarbons and nitrogen oxides released from vehicles could react photochemically to form ozone and other oxidants.

This explanation remains scientifically important because it clarifies that ground-level ozone is primarily a secondary pollutant. It is formed in the atmosphere when precursor gases react in the presence of sunlight. Ground-level ozone is harmful to human health, plants, and ecosystems. This differs from stratospheric ozone, which protects life on Earth from ultraviolet radiation. Students therefore need to understand that the same chemical substance can have different environmental meanings depending on its location in the atmosphere.

Photochemical smog also illustrates that air pollution is not always linear or simple. Ozone formation depends on interactions among nitrogen oxides, volatile organic compounds, sunlight, temperature, and atmospheric conditions. In some contexts, reducing volatile organic compounds may be more effective, while in other contexts reducing nitrogen oxides may be more important. This complexity shows that air pollution control should be based on scientific monitoring and contextual analysis rather than general assumptions (Sillman, 1999; Sillman & He, 2002).

This theme has strong implications for environmental science education. Photochemical smog can be used to show how invisible chemical reactions produce visible environmental consequences. Students can learn that air pollution is not merely a collection of dirty substances in the air, but a dynamic atmospheric process. This supports higher-order scientific thinking because learners must connect cause, process, and consequence. They need to understand how emissions become pollutants, how sunlight drives atmospheric reactions, and why urban areas with heavy traffic often experience poorer air quality.

The educational value of this topic also lies in its relevance to students' daily experiences. Many students are familiar with cars, motorcycles, traffic congestion, and hot weather. These experiences can become entry points for learning about nitrogen oxides, volatile organic compounds, ozone, and smog formation. By connecting local observations with scientific explanations, teachers can make environmental chemistry more meaningful and less abstract. Contextual science learning is especially useful when students are encouraged to interpret environmental phenomena through scientific concepts and evidence-based reasoning (Rohmaya, 2022; Zandroto & Sinaga, 2022).

Haagen-Smit's Scientific Contribution and Policy Relevance

The third theme highlights the broader significance of Haagen-Smit's work. His contribution was not limited to atmospheric chemistry; it also changed how governments and communities understood urban air pollution. Before his findings, smog was commonly associated with visible smoke, factory emissions, or waste burning. Haagen-Smit shifted the explanation toward vehicle exhaust and photochemical reactions. This scientific shift was important because it allowed policymakers to identify more specific intervention points.

Haagen-Smit's work illustrates how scientific evidence can influence environmental regulation. Once vehicle exhaust was identified as a major contributor to smog, governments could develop emission standards, improve fuel quality, require emission-control technologies, and monitor air quality more systematically. Catalytic converters, vehicle inspection systems, and stricter emission limits are examples of how scientific knowledge can guide technological and regulatory solutions (EEA, 2022; Ravi et al., 2023).

This theme demonstrates the relationship between science and society. Scientific research does not only produce knowledge for academic purposes; it can also inform responses to public problems. In Haagen-Smit's case, atmospheric chemistry became the basis for public health protection and environmental governance. His work is therefore valuable not only for environmental science, but also for science education, particularly in teaching the role of scientific evidence in public decision-making.

In the classroom, Haagen-Smit's work can be presented as a historical case of scientific problem-solving. Students can examine how a real environmental problem was observed, how scientific questions were developed, how chemical explanations were tested, and how the findings influenced policy. This approach can help students understand the nature of science. Science is not merely the memorization of facts, but a process of investigating causes, evaluating evidence, and applying knowledge to real-world problems (Sadler, 2004; Zeidler et al., 2019).

At the same time, Haagen-Smit's explanation needs to be placed within the broader context of contemporary pollution challenges. His work provides a powerful scientific explanation for photochemical smog, but modern air pollution involves more complex sources and systems. Vehicle emissions remain important, but they interact with industrial activity, waste burning, energy production, urban density, climate change, and human behavior. Haagen-Smit's contribution should therefore be understood as a foundational scientific explanation rather than a complete solution to all forms of modern air pollution.

Contemporary Mitigation Strategies for Vehicle Pollution Reduction

The fourth theme indicates that vehicle-related air pollution requires integrated mitigation strategies. Emission control remains necessary, but it is not sufficient. Contemporary solutions must combine cleaner vehicle technology, renewable energy, public transportation, sustainable urban planning, policy enforcement, and environmental education (IEA, 2023; IPCC, 2023).

Electric vehicles are often presented as a major solution because they reduce or eliminate tailpipe emissions. However, their environmental benefit depends on the source of electricity used for charging. If electric vehicles are powered by electricity generated from coal or other fossil fuels, pollution may shift from urban roads to power plants. Electric mobility should therefore be developed together with renewable energy transition. Clean transportation and clean energy systems need to support each other if emission reduction is to be effective.

Public transportation is another important strategy. A strong public transport system can reduce dependence on private vehicles and lower traffic-related emissions. However, public transportation must be accessible, affordable, reliable, safe, and convenient. Without these conditions, people may continue using private cars and motorcycles even when they understand that vehicles contribute to pollution. This shows that behavioral change depends not only on awareness, but also on infrastructure and policy support.

Urban planning also plays an important role. Cities designed primarily for private vehicles tend to increase fuel use, congestion, and emissions. In contrast, cities that support walking, cycling, and public transport can reduce dependence on private motorized travel. Low-emission zones, pedestrian areas, cycling lanes, and compact urban development can help reduce pollution by supporting cleaner mobility patterns (EEA, 2022; IPCC, 2023).

Regulatory enforcement remains essential. Emission standards, fuel quality control, vehicle inspection, and air quality monitoring can reduce pollutants when implemented consistently. Weak enforcement allows old or poorly maintained vehicles to continue releasing high levels of emissions. Pollution reduction therefore requires both technological innovation and strong governance.

Environmental education is also part of a comprehensive mitigation framework. Education can help students understand why pollution occurs, how it affects health, and what types of solutions are needed. However, pollution should not be presented only as an individual moral problem. Students should learn that air pollution is shaped by scientific, technological, economic, political, and behavioral factors. This broader understanding can support environmental citizenship and scientific literacy (Rohmaya, 2022; Sadler, 2004; Wisdayana et al., 2025; Zeidler et al., 2019).

Table 2. Comprehensive Summary of Literature Findings

No	Source	Focus of Literature	Main Finding	Relevance to the Review
1	Haagen-Smit (1952)	Photochemical smog chemistry	Hydrocarbons and nitrogen oxides react under sunlight to form ozone and oxidants.	Provides the historical and scientific foundation of the review.
2	Sillman (1999)	Ozone, NO _x , and VOC chemistry	Ozone formation depends on chemical regimes and precursor relationships.	Explains the complexity of ozone control.

No	Source	Focus of Literature	Main Finding	Relevance to the Review
3	Bai et al. (2022)	Health effects of traffic-related air pollution	Cleaner technologies reduce some emissions but do not eliminate health concerns.	Shows the continuing health relevance of traffic pollution.
4	Ravi et al. (2023)	Vehicle technology and emission regulation	Emission standards and vehicle technologies can reduce transport pollutants.	Connects scientific understanding with policy and technology.
5	WHO (2021, 2024)	Global air quality and health	Air pollution is associated with major global health risks.	Strengthens the public health justification for the review.
6	IEA (2023)	Electric vehicles and energy transition	Electric mobility must be supported by infrastructure and clean energy.	Expands mitigation strategies beyond vehicle technology.
7	IPCC (2023)	Climate change and transport	Transport emissions are linked to climate mitigation pathways.	Connects pollution reduction with climate action.
8	Sadler (2004); Zeidler et al. (2019)	Socio-scientific issue-based learning	Environmental issues can strengthen scientific reasoning and decision-making.	Supports the educational application of vehicle pollution topics.

Table 2 shows that the reviewed literature covers scientific, health, policy, energy, climate, and educational dimensions. Haagen-Smit's work provides the historical and chemical foundation, while more recent studies extend the discussion to public health, clean energy, climate action, and science education. This pattern supports the argument that vehicle-related air pollution is multidimensional. It cannot be explained only through chemistry, although chemistry remains essential for understanding its root mechanisms.

Table 3. Thematic Pattern from Literature Synthesis

Main Theme	Literature-Based Finding	Educational Relevance
Vehicle emissions	Fossil fuel combustion releases NO _x , VOCs, CO, and particulate matter.	Helps students connect daily transportation with chemical pollutants.
Photochemical smog	NO _x and VOCs react under sunlight to form ground-level ozone.	Provides a contextual basis for chemistry learning.
Health impacts	PM _{2.5} , NO ₂ , and ozone are linked to respiratory and cardiovascular risks.	Connects science learning with public health issues.
Policy response	Emission standards, catalytic converters, and monitoring systems can reduce pollution.	Shows how scientific evidence informs regulation.
Contemporary solutions	Electric vehicles, renewable energy, public transportation, and urban planning are needed.	Supports socio-scientific issue-based environmental education.

Table 3 summarizes the educational relevance of the review findings. Vehicle-related air pollution can support several science education goals. Students can learn chemical concepts through combustion and photochemical smog, biological and health concepts through pollutant exposure, and environmental policy through emission standards and air quality monitoring. They can also develop socio-scientific reasoning by comparing different mitigation strategies and evaluating their benefits and limitations.

Table 4. Conceptual Classification of Major Themes in the Reviewed Literature

Theme	Synthesis Level	Main Interpretation
Fossil fuel combustion	Dominant theme	Vehicle-related air pollution begins with the combustion of gasoline and diesel fuels.
Photochemical reaction	Dominant theme	NO _x and VOCs react under sunlight to form ground-level ozone and smog.
Regulatory response	Strong theme	Scientific evidence supports emission standards, fuel regulation, and vehicle technology.
Health impacts	Strong theme	Vehicle pollutants are associated with respiratory, cardiovascular, and environmental risks.
Renewable energy transition	Strong theme	Electric mobility requires clean energy systems to reduce pollution effectively.

Theme	Synthesis Level	Main Interpretation
Human behavior and urban planning	Supporting theme	Transport choices and city design influence vehicle dependence and exposure.
Environmental science education	Supporting theme	Air pollution can be used as a socio-scientific issue to strengthen scientific literacy.

Table 4 summarizes the major themes identified in the reviewed literature and their relative conceptual position in the synthesis. The classification does not represent quantitative scoring, but indicates the relative analytical importance of each theme in the discussion. Fossil fuel combustion and photochemical reaction are presented as dominant themes because they explain the scientific roots of vehicle-related air pollution. Regulatory response, health impacts, and renewable energy transition are categorized as strong themes because they connect scientific knowledge with public health and mitigation strategies. Human behavior, urban planning, and environmental science education are identified as supporting themes because they extend the discussion from atmospheric chemistry to social action and learning.

The distribution of themes suggests that air pollution literature often emphasizes chemical and regulatory dimensions more strongly than behavioral and planning dimensions. This does not mean that behavior and urban planning are less important. Rather, it indicates that scientific analysis often begins with emissions and atmospheric chemistry, while practical solutions require broader social and structural interpretation. For environmental science education, this pattern is useful because it shows students that scientific explanation and social action need to be connected.

Vehicle-Related Air Pollution as a Socio-Scientific Issue in Science Education

The synthesis shows that vehicle-related air pollution is highly suitable as a socio-scientific issue in science learning. Socio-scientific issues are real-world problems that involve scientific knowledge, social values, ethical considerations, and decision-making. Vehicle pollution meets these criteria because it involves atmospheric chemistry, health risks, transportation needs, economic constraints, technological choices, government policy, and individual behavior (Sadler, 2004; Zeidler et al., 2019).

Using vehicle-related air pollution as a learning context can help students move beyond memorization. Instead of only defining pollution, students can investigate how pollutants are produced, how they react in the atmosphere, how they affect health, and how different solutions work. For example, students can compare the benefits and limitations of electric vehicles, public transportation, cycling, walking, fuel regulation, and renewable energy. Through this process, students can develop scientific literacy, critical thinking, and environmental responsibility.

This approach is consistent with the broader goals of environmental science education. Environmental learning should not only encourage students to care for nature, but also help them understand environmental systems scientifically. Students need to learn that air pollution is caused by specific mechanisms and sustained by social systems. They also need to understand that solving pollution requires cooperation among individuals, communities, governments, industries, and scientists.

Haagen-Smit's photochemical smog theory can serve as a conceptual anchor in this learning process. His work provides a clear example of how scientific investigation can reveal hidden causes of environmental problems. Teachers can use this case to show how evidence-based explanations are developed and how scientific findings can influence public policy. This makes the topic useful for teaching both scientific content and the nature of science.

Implications for Environmental Science Learning

The findings have several implications for science learning. First, vehicle-related air pollution should be taught through systems thinking. Students should understand the relationship between fuel combustion, emissions, atmospheric reactions, health effects, regulation, and behavior. This can prevent oversimplified thinking, such as assuming that pollution is caused only by smoke or that electric vehicles automatically solve all pollution problems.

Second, teachers can apply contextual learning strategies. Vehicle pollution is close to students' daily experiences because many students observe traffic, motorcycles, cars, and road congestion. Teachers can begin

with these familiar observations and then guide students toward scientific explanation. This process helps connect everyday experience with academic concepts. Contextual learning can support students in understanding science as knowledge that explains real environmental phenomena (Rohmaya, 2022; Zandroto & Sinaga, 2022).

Third, air pollution learning should include critical evaluation of solutions. Students should be encouraged to ask why certain solutions work, under what conditions they work, and what limitations they have. For instance, electric vehicles reduce tailpipe emissions but require clean electricity. Public transportation can reduce private vehicle use but requires strong infrastructure. Tree planting can support environmental quality but cannot replace emission reduction. This type of analysis can strengthen students' scientific reasoning and decision-making.

Fourth, environmental education should integrate personal and policy-level responsibility. Individual actions such as walking, cycling, reducing unnecessary vehicle use, and supporting clean habits are important. However, large-scale air pollution reduction also requires emission standards, energy transition, public transportation investment, and urban planning. Students should understand that environmental citizenship involves both personal behavior and participation in broader social change.

Overall, the synthesis shows that Haagen-Smit's scientific contribution remains relevant for contemporary environmental science education. His explanation of photochemical smog provides a strong foundation for understanding vehicle-related air pollution. However, modern pollution challenges require an expanded framework that includes clean energy, transport reform, regulation, urban planning, behavioral change, and education. This integrated perspective can help science education prepare students to understand and respond to environmental problems in a more scientific, critical, and responsible way.

Pedagogical Integration of Vehicle-Related Air Pollution in Environmental Science Learning

The findings of this review indicate that vehicle-related air pollution can be translated into environmental science learning through a socio-scientific issue framework. In this framework, students are not only introduced to air pollution as an environmental problem, but are also guided to understand the scientific mechanisms, health consequences, technological alternatives, and policy responses related to the issue. Haagen-Smit's photochemical smog theory can serve as a conceptual anchor because it helps students connect vehicle emissions with atmospheric chemical reactions and the formation of secondary pollutants such as ground-level ozone.

In classroom learning, the topic can be introduced through students' everyday experiences with traffic, motorcycles, cars, and urban air quality. Teachers may begin by asking students to identify common sources of air pollution in their surroundings, then guide them to examine how gasoline and diesel combustion release nitrogen oxides, volatile organic compounds, carbon monoxide, and particulate matter. This learning process can help students distinguish between primary pollutants that are directly emitted from vehicles and secondary pollutants that are formed through atmospheric reactions.

The topic can also be developed into inquiry-based and discussion-based learning activities. For example, students may construct concept maps of photochemical smog formation, analyze cases of traffic-related air pollution near schools or urban roads, compare the strengths and limitations of electric vehicles and public transportation, or debate policy options such as emission standards, low-emission zones, and renewable energy transition. Through these activities, students are encouraged to apply scientific concepts, evaluate evidence, consider social and technological constraints, and propose realistic mitigation strategies.

This pedagogical integration supports the development of scientific literacy because students learn to explain environmental phenomena scientifically, evaluate possible solutions, and make responsible decisions. Therefore, vehicle-related air pollution is not only relevant for teaching environmental chemistry, but also for strengthening socio-scientific reasoning and environmental citizenship. In this sense, the educational value of Haagen-Smit's theory lies not only in its historical contribution to atmospheric chemistry, but also in its potential to make science learning more contextual, interdisciplinary, and socially meaningful.

CONCLUSION

This integrative literature review shows that vehicle-related air pollution can be understood as both an atmospheric chemistry problem and a contextual issue for environmental science education. The synthesis

indicates that fossil fuel combustion releases primary pollutants, including nitrogen oxides, volatile organic compounds, carbon monoxide, and particulate matter, while secondary pollutants such as ground-level ozone are formed through photochemical reactions involving nitrogen oxides, volatile organic compounds, and sunlight. Haagen-Smit's photochemical smog theory remains significant because it explains the chemical relationship between vehicle exhaust and smog formation and provides a conceptual bridge between scientific explanation, environmental policy, and public understanding. In environmental science education, vehicle-related air pollution can function as a socio-scientific issue that connects chemistry, public health, clean energy, transportation policy, urban planning, behavioral change, and environmental citizenship. This study is limited by its literature-based design because it does not include classroom intervention, student data, teacher perspectives, or local air quality measurement. Future research should examine the effectiveness of experimental socio-scientific issue-based learning on vehicle-related air pollution, classroom implementation of Haagen-Smit-based learning activities, development of instructional modules on photochemical smog, and students' misconceptions about vehicle emissions, ozone formation, and air pollution mitigation.

References

- Bai, X., Chen, H., & Oliver, B. G. (2022). The health effects of traffic-related air pollution: A review focused the health effects of going green. *Chemosphere*, 289, 133082. <https://doi.org/10.1016/j.chemosphere.2021.133082>
- Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., ... Forouzanfar, M. H. (2017). Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: An analysis of data from the Global Burden of Diseases Study 2015. *The Lancet*, 389(10082), 1907–1918. [https://doi.org/10.1016/S0140-6736\(17\)30505-6](https://doi.org/10.1016/S0140-6736(17)30505-6)
- Cooper, H. M. (1988). Organizing knowledge syntheses: A taxonomy of literature reviews. *Knowledge in Society*, 1(1), 104. <https://doi.org/10.1007/BF03177550>
- EEA. (2022, November 23). *Air quality in Europe 2022*. European Environment Agency. <https://www.eea.europa.eu/en/analysis/publications/air-quality-in-europe-2022>
- Haagen-Smit, A. J. (1952). Chemistry and Physiology of Los Angeles Smog. *Industrial & Engineering Chemistry*, 44(6), 1342–1346. <https://doi.org/10.1021/ie50510a045>
- HEI. (2022, June 16). *Systematic Review and Meta-analysis of Selected Health Effects of Long-Term Exposure to Traffic-Related Air Pollution*. Health Effects Institute. Health Effects Institute. <https://www.healtheffects.org/publication/systematic-review-and-meta-analysis-selected-health-effects-long-term-exposure-traffic>
- IEA. (2023, April 26). *Global EV Outlook 2023 – Analysis*. International Energy Agency. International Energy Agency. <https://www.iea.org/reports/global-ev-outlook-2023>
- IPCC. (2022). *Chapter 10: Transport*. Intergovernmental Panel on Climate Change. <https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-10/>
- IPCC. (2023). *AR6 Synthesis Report: Climate Change 2023*. Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change. <https://www.ipcc.ch/report/ar6/syr/>
- Mabsutsah, N., & Yushardi, Y. (2022). Analisis Kebutuhan Guru terhadap E Module Berbasis STEAM dan Kurikulum Merdeka pada Materi Pemanasan Global. *JURNAL PENDIDIKAN MIPA*, 12(2), 205–213. <https://doi.org/10.37630/jpm.v12i2.588>
- Muttaqiin, A. (2023). Pendekatan STEM (Science, Technology, Engineering, Mathematics) pada Pembelajaran IPA Untuk Melatih Keterampilan Abad 21. *JURNAL PENDIDIKAN MIPA*, 13(1), 34–45. <https://doi.org/10.37630/jpm.v13i1.819>
- OECD. (2023). *PISA 2022 Results (Volume I): The State of Learning and Equity in Education*. PISA. <https://doi.org/10.1787/53f23881-en>

- Ravi, S. S., Osipov, S., & Turner, J. W. G. (2023). Impact of Modern Vehicular Technologies and Emission Regulations on Improving Global Air Quality. *Atmosphere*, 14(7). <https://doi.org/10.3390/atmos14071164>
- Rohmaya, N. (2022). Peningkatan Literasi Sains Siswa Melalui Pembelajaran IPA Berbasis Socioscientific Issues (SSI). *JURNAL PENDIDIKAN MIPA*, 12(2), 107–117. <https://doi.org/10.37630/jpm.v12i2.553>
- Sadler, T. D. (2004). Informal reasoning regarding socioscientific issues: A critical review of research. *Journal of Research in Science Teaching*, 41(5), 513–536. <https://doi.org/10.1002/tea.20009>
- Sillman, S. (1999). The relation between ozone, NO_x and hydrocarbons in urban and polluted rural environments. *Atmospheric Environment*, 33(12), 1821–1845. [https://doi.org/10.1016/S1352-2310\(98\)00345-8](https://doi.org/10.1016/S1352-2310(98)00345-8)
- Sillman, S., & He, D. (2002). *Some theoretical results concerning O₃-NO_x-VOC chemistry and NO_x-VOC indicators*. <https://doi.org/10.1029/2001JD001123>
- Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333–339. <https://doi.org/10.1016/j.jbusres.2019.07.039>
- Torraco, R. J. (2005). Writing Integrative Literature Reviews: Guidelines and Examples. *Human Resource Development Review*, 4(3), 356–367. <https://doi.org/10.1177/1534484305278283>
- WHO. (2021). *WHO global air quality guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. World Health Organization. <https://www.who.int/publications/i/item/9789240034228>
- WHO. (2024). *Ambient (outdoor) air pollution*. World Health Organization. [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health)
- Wisdayana, N., Achyani, A., Aththibby, A. R., & Pratiwi, D. (2025). Integrasi Literasi Sains pada Bahan Ajar Berbasis Socio Scientific Issues. *JURNAL PENDIDIKAN MIPA*, 15(1), 40–50. <https://doi.org/10.37630/jpm.v15i1.2164>
- Zandroto, A. V., & Sinaga, K. (2022). Analisis Kemampuan Literasi Kimia Siswa Pada Materi Senyawa Hidrokarbon Melalui Pendekatan Kontekstual. *JURNAL PENDIDIKAN MIPA*, 12(2), 349–358. <https://doi.org/10.37630/jpm.v12i2.596>
- Zeidler, D. L., Herman, B. C., & Sadler, T. D. (2019). New directions in socioscientific issues research. *Disciplinary and Interdisciplinary Science Education Research*, 1(1), 11. <https://doi.org/10.1186/s43031-019-0008-7>