บทความฟื้นวิชา **Review Articles**

การทบทวนอย่างเป็นระบบของนวัตกรรมระดับท้องถิ่นและระดับโลก เพื่อบรรเทาปัญหา PM2.5 ในประเทศไทย

A Systematic Review of Local and Global innovations for Mitigation of PM2.5 in Thailand

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บทคัดย่อ

มลพิษ PM2.5 ได้กลายเป็นปัญหาสิ่งแวดล้อมและสาธารณสุขที่สำคัญ โดยเฉพาะในพื้นที่เมืองและเขตเกษตรกรรมของประเทศไทย การทบทวนวรรณกรรมเชิงระบบนี้ได้สำรวจแหล่งกำเนิดหลักของฝุ่น PM2.5 ผลกระทบต่อสุขภาพและนวัตกรรมล่าสุด รวมถึงนโยบายแหล่งกำเนิดหลักของฝุ่น PM2.5 ที่พบจากการศึกษานี้ คือ การปล่อยมลพิษจากยานพาหนะ การเผาชีวมวล และกิจกรรมอุตสาหกรรม โดยฝุ่นละอองทุติยภูมิยังมีบทบาทสำคัญต่อมลพิษข้ามพรมแดน งานวิจัยนี้ยังประเมินประสิทธิภาพของเทคโนโลยีการกรองอากาศหลายประเภท เช่น แผ่นกรอง HEPA เมมเบรนนาโนไฟเบอร์ และแผ่นกรองแบบ Electrospun รวมถึงแบบจำลองการพยากรณ์โดยใช้ปัญญาประดิษฐ์ (AI) และเครือข่ายเซนเซอร์ไร้สาย แม้จะมีพัฒนาการด้านเทคโนโลยีที่มากขึ้นแต่ยังไม่ได้นำไปใช้มาก เนื่องจากต้นทุนสูงความต้องการการใช้พลังงานและการเผยแพร่สู่สาธารณชนน้อย การบังคับใช้นโยบายเข้มงวด การส่งเสริมนวัตกรรมยังไม่ยั่งยืนและมีต้นทุนต่ำ ขาดการสื่อสารข้อมูลคุณภาพอากาศที่เป็นปัจจุบันและขาดประสิทธิภาพ การศึกษานี้จึงทำเพื่อเสนอข้อมูลสำหรับนักวิจัย ผู้กำหนดนโยบาย และผู้สนใจ เพื่อพัฒนากลยุทธ์ที่มีประสิทธิภาพในการลดมลพิษทางอากาศและปกป้องสุขภาพประชาชน

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Abstract

PM2.5 pollution has created problems of environmental and public health, including in urban and agricultural regions of Thailand. This study presents a systematic review exploring the major sources of PM2.5, its impact on human health, as well as innovations and policies. The primary sources of PM2.5 include traffic emissions, biomass burning, and industrial activities, with secondary aerosols contributing significantly to transboundary pollution. The review evaluated the effectiveness of various air purification technologies, predictive models using AI and wireless sensor networks. Despite promising technological developments, widespread implementation faces challenges such as high costs, energy demands, and limited public awareness. Strengthening policy enforcement, promoting low-cost sustainable innovations, and enhancing real-time air quality communication are essential. This review recommends that researchers, policymakers, and community workers collaborate to develop effective strategies to mitigate PM2.5 pollution and protect health of population.

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Introduction

Air pollution, driven by rapid growth of global population and industrialization, poses major threats to human health, ecosystems, and the climate. According to the World Health Organization (WHO), 90% of the global population breathes air that exceeds safety standards, contributing to 4.2 million premature deaths, annually(1,2). Key pollutants include sulfur dioxide, carbon monoxide, ozone, nitrogen dioxide, and especially fine particulate matter smaller than 2.5 micrometers (PM2.5) penetrate into the lungs and bloodstream (2). PM2.5 consists of substances such as sulfates, nitrates, organic carbon, trace metals, and persistent organic pollutants(3). Major sources include traffic emissions, industrial activity, coal and biomass combustion, and transboundary haze, with regional variations, influenced by geography and weather patterns(4). Due to its toxicity and small size, PM2.5 is more difficult to be controlled comparing with larger particulates. WHO recommends to expose PM2.5 not over than to 5 μg/m³, annually and 15 μg/m³, daily. The exposure is associated with chronic diseases such as COPD, ischemic heart disease, stroke, and lung cancer(5,6), and even less exposure of PM2.5 levels gains in life expectancy.

Air Pollution in the Thai Context

In Thailand, a rise in vehicle uses and a decline in public transit over recent years have worsened air quality, particularly in urban areas like Bangkok where traffic, biomass burning, and industrial emissions are major contributors(7). Although PM2.5 levels temporarily decreased during the COVID-19 lockdown, pollution rebounded post-2022, with sustained hazardous Air Quality Index (AQI) readings and worsening forecasts beyond 2025. In response, the Pollution Control Department has implemented strategies to decentralize pollution management, promote electric vehicles, and enhance air quality monitoring. However, outcomes remain limited, and PM2.5 concentrations are still dangerously high.

To address these challenges, Thai researchers have introduced innovative technologies such as the "Fahsai Mini"; purification tower, developed by the Research & Innovation for Sustainability Center (RISC), alongside emerging applications of artificial intelligence for air quality forecasting. This systematic review examines how to mitigate PM2.5 and its predict both in domestic and global innovations evaluating their effectiveness, scalability, and policy relevance in the Thai context.

Methodology

This review employed a systematic approach to examine the sources and health impacts, innovations, and policy responses to mitigate PM2.5 with a focus on Thailand and global.

A literature search was conducted using databases such as PubMed, ScienceDirect, MDPI, ThaiJO, Springer, IEEE Xplore, PIER, and official government sources.

Keywords were “PM2.5,” “air pollution,” “innovations,” “air purifiers,” “predictive modeling,” and “Thailand,” covering publications from 2009 to 2025. Selected studies, articles and official reports were peer-reviewed relating to sources of PM2.5, health effects, innovations, and public awareness, either within Thailand or global. Theses, dissertations, and non-peer-reviewed materials were excluded.

Extracted data was categorized into five thematic areas; sources, health impacts, innovations, public awareness, and policy. An analysis based on their effectiveness, feasibility, and relevance to the Thai context.

Literature Review

PM2.5 Emission Sources in Thailand

PM2.5 emissions in Thailand originate from many sources, which significantly vary by region. In the Bangkok Metropolitan Region, the primary contributors are traffic emissions (43.7%), agricultural field burning (24.0%), and industrial factories (4.46%)[8]. In contrast, rural area experience higher emissions from wildfires, biomass combustion, particularly the burning of rice straw and sugarcane, and transboundary haze. In 2025, urban biomass combustion has been identified as the leading source of PM2.5, according to Associate Professor Dr. Surat Bualert[9].

Traffic emissions are a significant contributor to PM2.5 pollution, containing notable of trace elements such as tin (Sn), antimony (Sb), and chromium (Cr) detected. In Bangkok, small vehicles constitute a primary source of these emissions. A study in Kamphaeng Phet Province demonstrated a strong positive correlation between daily traffic volume and PM2.5 concentrations.[10] Gasoline vehicles tend to emit more organic carbon (OC), while diesel vehicles emit higher levels of elemental carbon (EC). However, slow-moving diesel vehicles may also release higher OC levels, producing OC:EC ratios comparable to those of gasoline vehicles. Similar trends have been observed in India, where the increasing ownership of motorcycles, scooters, and cars has driven up traffic-related PM2.5 emissions[11], reflecting the impact of urbanization and industrial development[12].

In rural areas, open burning, particularly during the dry winter season-remains a major source of PM2.5. In Chiang Mai, peak smoke periods yielded a PM2.5 concentration of 59.3 $\mu g/m^3$ based on PMF-resolved analysis[13]. The burning of sugarcane and rice straw significantly contributes to OC and EC emissions. A similar pattern is observed in southwest China, where urban centers such as Chengdu emit high levels of OC, EC, and trace ions (K^+, Cl^-) due to biomass combustion[3]. In Thailand’s Khon Kaen Province, a key sugarcane production area, burning activities generate dust particles ranging from 0.1 to 50 microns in diameter.

Although industrial activities contribute relatively to PM2.5 in Bangkok due to the city's limited number of factories, provinces with higher industrial density, such as Pathum Thani, report significantly elevated PM2.5 concentrations[14]. Globally, coal-fired industries release harmful pollutants such as EC, zinc (Zn), copper (Cu), tin (Sn), antimony (Sb), thallium (Tl), and lead (Pb), with Sn, Sb, and Tl being among the most significant contributors. These emission result from sulfur impurities reacting with oxygen to form Sulfur dioxide (SO_2)[15]. In China, iron and steel industries also emit toxic metals such as iron (Fe), manganese (Mn), and chromium (Cr), as well as polycyclic aromatic hydrocarbons (PAHs), many of which are carcinogenic[3,14]. While industrial emissions are a dominant source of PM2.5 in China, agricultural burning remains more central to Thailand’s air quality concerns.

Secondary sources of PM2.5, such as nitrates and sulfates, result from atmospheric chemical transformations. Nitrate formation depends on the presence of NO_3^- and NH_4^+, relative humidity, ambient temperature, and nighttime photochemistry, typically leading to the formation of ammonium nitrate (NH_4NO_3). Sulfate formation, on the other hand, is influenced by SO_4^{2-} and NH_4^+, and is more prominent in summer due to higher concentrations of nitric acid (HNO_3). The formation of ammonium sulfate ($(NH_4)_2SO_4$) depletes ammonia (NH_3), reducing its availability to form NH_4NO_3. In Seoul, secondary aerosols are largely transported from eastern Chinese provinces such as Jiangsu and Shandong, while maritime SO_2 emissions also contribute(16). A similar pattern is observed in Chiang Mai, where secondary sulfates from the Indian subcontinent constitute a major source of PM2.5(13).

Geography and meteorology also play a critical role in PM2.5 dispersion. For example, Chengdu's mountainous terrain trap pollutants, particularly during the winter months(17). Stagnant weather conditions in winter or spring reduce atmospheric mixing and inhibiting PM2.5 dispersal, while summer rainfall helps remove particulates through precipitation. However, wind can have mixed effects: while it can disperse pollutants, it may also carry them to boarder areas. In Kamphaeng Phet, for instance, wind coupled with heavy traffic has been found to exacerbate PM2.5 levels(10).

Health Effects and Current PM2.5 Conditions in Thailand

PM2.5 particles, due to their ultrafine size, can penetrate deep into the lungs and enter the bloodstream, leading to significant health risks. Exposure is linked to respiratory diseases like COPD, asthma, and lung cancer, as well as cardiovascular conditions such as endothelial dysfunction, elevated blood pressure, acute coronary syndrome (ACS), and ischemic heart disease (IHD) (1). Between October 2024 and January 2025, Thailand's Ministry of Public Health reported over 1,048,015 health cases related to PM2.5 exposure, including 442,073 cases of dermatitis, 357,104 cases of allergic conjunctivitis, 226,423 cases of COPD, 18,336 asthma cases, 4,051 ACS cases, and 28 pollution-related illnesses(18).

At the cellular level, PM2.5 induces oxidative stress by generating reactive oxygen species (ROS), damage lipids, proteins, and DNA [1]. Even low concentrations can provoke inflammatory responses in healthy lungs. A 10 $\mu g/m^3$ increase in exposure is associated with a 33% rise in coughing and a 23% increase in phlegm production.(6) While a definitive link between PM2.5 and asthma has not been fully established, evidence suggests a strong association through inflammation and immune system activation. A study in Taiwan found that prenatal exposure to PM2.5 concentrations above 93 $\mu g/m^3$ significantly increased the risk of asthma in children(4).

Cardiovascular damaged from PM2.5 occurs through oxidative stress and disruption of the autonomic nervous system (ANS), potentially leading to arrhythmias. Endothelial cells respond to PM2.5 by releasing adhesion molecules that attract leukocytes and platelets, promoting thrombus formation-a process associated with increased thrombin activity(1).

Other organs, including the eyes and skin, are also vulnerable. The eye's precorneal film is sensitive, making it prone to irritation, conjunctivitis, and glaucoma. Prolonged exposure to nitrates in PM2.5 has been associated with age-related macular degeneration (AMD). In India, commuters using open vehicles frequently report eye redness, irritation, and dryness(5).

Skin conditions such as atopic dermatitis and premature aging are linked to direct dermal contact or systemic absorption of airborne pollutants[19].

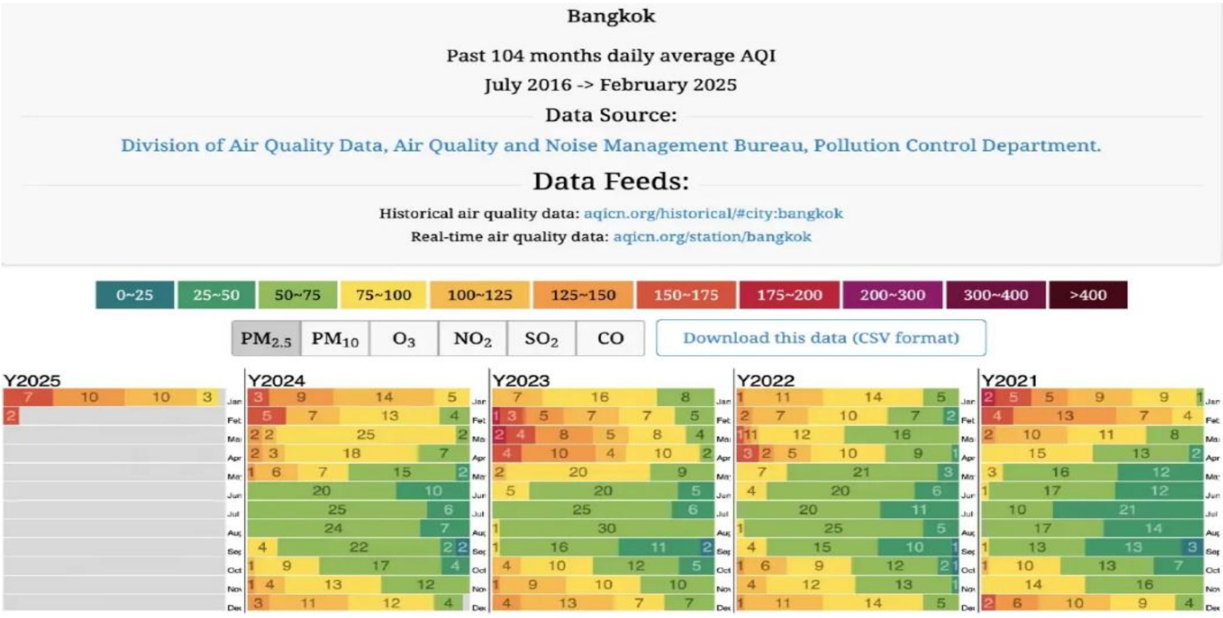

Figure 1 Statistics of daily average AQI from July 2016 to February 2025[20]

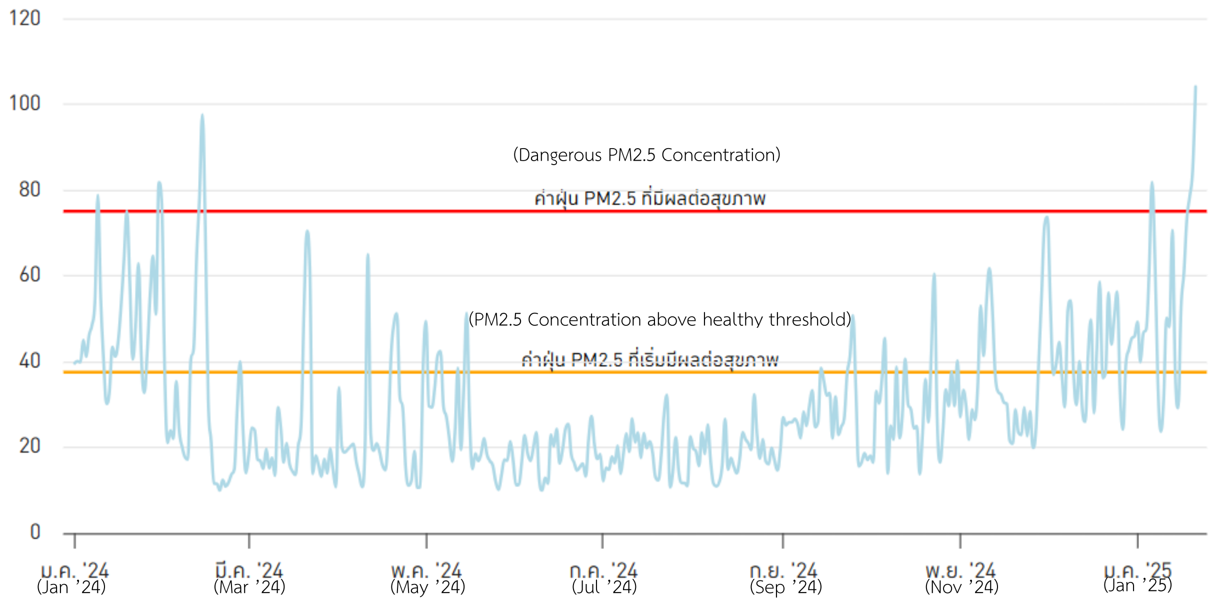

Figure 2 The daily average concentration of PM2.5 (μg/m3)[21]

Regarding current conditions, data from July 2016 to February 2025 indicate that PM2.5 levels in Thailand have remained above healthy thresholds for extended periods. In early 2025, seven consecutive days recorded AQI levels between 150-175, followed by 20 days between 100–150, indicating prolonged exposure to dangerous PM2.5 concentrations. While PM2.5 levels decreased during the COVID-19 pandemic, they have since worsened. In 2023, 51 provinces recorded PM2.5 levels exceeding 51 μg/m³ for three consecutive days, surpassing Thailand's daily limit of 50 μg/m³[22]. On January 21, 2025, PM2.5 concentrations surged above 100 μg/m³. As of the study period, Thailand ranks as the 36th most polluted country globally, according to IQAir. Previous studies by Associate Professor Dr. Witsanu Attavanich estimated the social cost of PM2.5 at 2.173 trillion baht for Thai residents, escalating to over 4.616 trillion baht when accounting for all air pollutants[23].

Actions Against PM2.5

Thailand employs a multi-pronged approach to address PM2.5 pollution, integrating national policy, technological innovation, and community engagement. According to the Government Public Relations Department, core strategies include promoting alternatives to biomass burning, regulating industrial emissions, controlling vehicle pollution, disseminating accurate public information, and investing in forecasting technologies[24].

In 2019, the Pollution Control Department introduced three key measures: (1) enhancing provincial response capacity, (2) reducing emissions at the source, and (3) strengthening legal enforcement and real-time monitoring. Additionally, the Department of Provincial Administration proposed a simplified "Communicate-Prevent-Tackle" framework to streamline local-level-action.

Recognizing transportation as a major contributor to PM2.5 pollution, Thailand has implemented policies promoting electric and hybrid vehicles, expanding public transit, and encouraging the use of natural gas vehicles compliant with Euro six standards. These initiatives are parts of Thailand’s 20-Year Sustainable Transport Development Plan (Office of the Permanent Secretary, Ministry of Transport, 2021).

Industrial emissions are addressed through a tiered urgency approach. High-risk facilities-such as fossil fuel plants and metalworking operations are required to implement upgrades and undergo regular inspections. Long-term measures involve updating regulations and deploying tools such as the Pollutant Release and Transfer Register (PRTR) and the Pollution Online Monitoring System (POMS) for real-time tracking.

In wide agricultural areas, efforts focus on discouraging biomass burning. Authorities have introduced public education campaigns and voluntary reporting systems to detect and respond to illegal burning activities. Similarly, construction sites are required to implement dust control measures, including barrier walls, tire-washing stations, and proper covering of materials.

At the international level, Thailand is a signatory to the ASEAN Transboundary Haze-Free Roadmap, which targets regional air pollution resulting from cross-border forest fires and agricultural burning[8].

Community-level actions are equally vital. During high-pollution periods, residents are advised to stay indoors, seal windows, and use air purifiers. In high-risk areas, N95 masks are recommended, shown to reduce particulate inhalation and help lower blood pressure[1]. Mobile applications such as AirVisual and Air4Thai provide real-time air quality data, enabling residents to make informed decisions[25].

Public Awareness of PM2.5 in Thailand

Public awareness of PM2.5 is a key driver of protective behavior. A study in Klang Village, Pathum Thani, found high level of awareness and preventive action among residents, consistent with findings from a 2016 study in Bangkok[26]. While factors such as gender and age influenced behavior, the importance of broad-based communication across all demographics was emphasized.

Another survey found only moderate knowledge of PM2.5 among respondents (average score: 59.59%), although awareness of preventive practices-such as reducing smoking, avoiding outdoor exposure, and frequent cleaning-was high. Attitude emerged as the strongest predictor of preventive behavior. Misinformation and limited access to verified information sources were cited as barriers. Additionally, individuals in low-exposure occupations were less concerned, whereas students, civil servants, and educated professionals demonstrated greater awareness(27). A 2020 study in Lampang, Thailand's most polluted province-showed that over 55% of participants possessed strong PM2.5 knowledge and engaged in protective behavior. Similar findings from a study in Bangkok in year 2014 highlighted that when air pollution is perceived as a daily health threat, public compliance improves. However, practical mitigation-such as air purifier use-was only moderately adopteddue to cost and implementation complexity(28).

Air Purifiers studies in Thailand

To mitigate the increasing health risks posed by PM2.5, various individuals and research groups in Thailand have developed innovative air purification solutions for both indoor and outdoor environments. Urban populations typically spend 60% to 90% of their time indoors, with vulnerable groups such as the elderly, pregnant women, and individuals with chronic illnesses, spending even more time inside. Indoor PM2.5 can originate from multiple sources: indoor emissions (e.g., cooking fumes, household cleaning agents, cigarette smoke, and pet allergens), infiltration from outdoor pollution (e.g., vehicle emissions), and the formation of secondary organic aerosols (SOA)(29,30).

Recognizing the complexity of these indoor air pollutants, Dr. Boonyang Plangklang has examined four core air purification technologies: HEPA filtration, ozone generation, ultraviolet (UV) radiation, and ionization.

• Ozone (O_3) is recognized for its high oxidation potential (2.07 eV), which enables it to destroy pathogens such as bacteria and fungi; a property acknowledged by the U.S. Environmental Protection Agency since 1976.

• HEPA filters, made of tightly woven fiberglass, can capture particles larger than 0.3 microns. They are commonly used in appliances such as air purifiers, air conditioners, and vacuum cleaners. HEPA filters are categorized by increasing efficiency levels (E10-E12, H13-H14, U15-U17) and can be maintained through brushing or vacuuming.

• UVC radiation (ultraviolet germicidal irradiation or UVGI) works by disrupting microbial DNA and is applicable for air, liquid, and surface disinfection. It is highly efficient, non-thermal, and safe for home use.

• Ionizers emit negative ions, which can improve mood and alleviate respiratory symptoms. However, they may produce ozone as a byproduct, raising health concerns with prolonged exposure.

Dr. Boonyang's prototype combines all four technologies into a single integrated device. The purifier features automated filtering, sterilization, motion detection, programmable timers, and a real-time monitoring app ("Air4U") for tracking PM2.5 levels and humidity. Test results showed that the device could maintain indoor PM2.5 levels below 37 µg/m³ and eliminate 99% of airborne bacteria and fungi under diverse environmental conditions(31).

On a public scale, Thailand's Research & Innovation for Sustainability Center (RISC) developed large-scale air purifiers, including the "Fresh One," "Fahsai 1," "Fahsai 2," and the more compact "Fahsai Mini." Since 2020, these systems have been installed in locations such as True Digital Park and the University of Phayao(32). The Fahsai Mini, capable of filtering 120,000 m³ of air per hour, covers an area of 20–50 meters. It uses water-based filtration to trap PM2.5 and requires fewer filter replacements. Additionally, it integrates UVGI for disinfection and releases clean air at human breathing height(33).

Air Purifier Studies Outside Thailand and Advances in Technology

International research has evaluated the effectiveness of air purifiers in diverse environments. Kai-Chung et al. tested a HEPA-based Samsung AX9000 purifier in Fresno homes, showing significant reductions in PM2.5 and endotoxins, though short-term PM2.5 spikes occurred due to airflow turbulence(30). In the UK, Cooper et al. modeled the health benefits of air purifiers in cooking-related settings. High-efficiency purifiers (82.5%) could result in over 34 million years of life gained (YLG), translating to 201 extra days for males and 175 for females(34). Reducing PM2.5 by just 3 µg/m³ could add 2-3 months to life expectancy.

To address the energy limitations of conventional purifiers, passive technologies have emerged. Studies on nanofiber membranes, especially polyacrylonitrile (PAN)-demonstrated filtration efficiency exceeding 99%, with high light transmittance and low pressure drops(35). These filters also maintained performance in humid conditions(36). Electrospun Ag-TiO_2 nanorod filters exhibited greater than 90% efficiency and the ability to degrade toluene, with silver nanoparticles enhancing catalytic reactivity(37).

Meanwhile, AI-powered models such as CNN-LSTM have revolutionized PM2.5 forecasting. By integrating environmental variables (e.g., humidity, wind speed), CNN-LSTM models significantly outperform traditional univariate approaches in terms of predictive accuracy and speed(38). Unlike conventional methods such as gravimetric analysis or the Federal Reference Method (FRM), which are time-consuming and expensive, AI enables real-time, adaptive forecasting(39).

Sensor-based innovations, particularly Wireless Sensor Networks (WSNs), now support real-time monitoring in high-risk areas. When combined with low-cost sensors (e.g., PurpleAir, Nova SDS) and remote sensing technologies (e.g., drones, satellites), these tools provide dense spatial coverage and enable rapid deployment. While low-cost sensors offer scalability, they face challenges in precision due to environmental interference. The convergence of AI with WSNs and energy-efficient components is advancing scalable, intelligent PM2.5 monitoring systems for proactive pollution control(39).

Summary of Key Findings

PM2.5 sources in Thailand differ by region. In Bangkok, traffic emissions contribute approximately 43.7% of PM2.5 levels, while in rural areas, agricultural burning accounts for around 24%(8). Health impacts are extensive, affecting respiratory, cardiovascular, neurological, ocular, and dermatological systems. Between October 2024 and January 2025, over one million PM2.5-related health cases were reported(19). Technological responses such as HEPA purifiers, PAN nanofiber filters, Ag-TiO_2 electrospun filters, and AI-driven models like CNN-LSTM have demonstrated strong potential in reducing and predicting PM2.5 exposure(36,39). However, barriers remain, including high costs, energy demands, limited public awareness, and weak policy enforcement. Knowledge levels also vary, with higher awareness in polluted areas and among well-educated individuals, while public understanding in Bangkok remains moderate overall(27).

Discussion

Critical Analysis

This review demonstrates strong credibility by drawing upon a wide range of peer-reviewed literature, government reports, and international data sources. However, certain findings derived from contexts such as India, China, and the United States may not be fully transferable to Thailand, due to differences in industrial structures, regulatory frameworks, and technological infrastructure. Additionally, the review gives limited attention to long-term cost-benefit analysis, equitable access to clean air technologies, and behavioral interventions beyond public awareness. Technological limitations are also evident; while innovations like advanced air purifiers and AI predictive models show promise, their widespread adoption is hindered by high costs, energy demands, and the insufficient coverage of sensor networks in Thailand.

Interpretation

PM2.5 pollution remains a critical threat to public health in Thailand. This review confirms the strong links between major pollution sources-traffic, burning, and industry-and the increased of disease burden and economic loss. Post-COVID, PM2.5 levels have rebounded, reflecting global urban trends. Scalable technologies such as passive nanofiber filters and AI monitoring systems offer promise. However their success depends on infrastructure readiness, public engagement, and government enforcement.

Implications

To reduce PM2.5, Thailand must strengthen emission regulations across transport, agriculture, and industry. Subsidies for affordable, energy-efficient air filtration systems are essential for equitable access. Investments in AI-based monitoring infrastructure can facilitate real-time interventions. Policy should integrate urban greening, low-cost community sensors, and strengthen enforcement of burning and emission bans. Future research should focus on developing low-energy, affordable air purifiers and conducting longitudinal studies on the long-term impacts of PM2.5. Local calibration of AI models will enhance predictive reliability, while behavioral research is needed to strengthen public compliance.

Limitations and Recommendations

Key limitations include limited air quality sensor coverage-particularly in rural areas and the high energy use of current air cleaning technologies. Public understanding of PM2.5 risks remains uneven, and enforcement of regulations is weak. To address these gaps, Thailand should:

- Expand wireless sensor networks nationwide for real-time, high-resolution PM2.5 tracking.
- Subsidize passive filters such as PAN nanofiber screens for vulnerable populations.
- Promote verified health information through targeted social media campaigns to combat misinformation.
- Mandate emission reporting using tools like PRTR and enforce through routine audits.
- Support R&D in sustainable filtration, prioritizing biodegradable and solar-powered designs.

These measures will foster scalable, inclusive, and sustainable solutions to Thailand's escalating air pollution crisis.

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