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The future of environmental health modeling: leveraging artificial intelligence to combat air pollution challenges

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Abstract

Recent advancements in artificial intelligence (AI), particularly large-scale multimodal models, are transforming various sectors by surpassing human performance in a wide range of tasks. Although AI is increasingly applied to tackle environmental issues such as air pollution, its use in analyzing the relationship between pollution and human health remains limited. Given AI's growing capabilities in real-time human-environment monitoring, multimodal data integration, predictive health modeling, and intelligent data processing, this perspective explores AI's potential in advancing research on the health effects of air pollution. We emphasize the role of AI in enabling personalized risk assessments, supporting informed decision making, and uncovering previously hidden mechanisms linking the environment to health. By synthesizing current research, this article highlights how AI can accelerate scientific discovery and inform targeted public health interventions and policies, offering a paradigm shift in addressing this pressing global challenge.

Keywords: AI-driven, human health, air pollution, modeling and analysis

INTRODUCTION

Air pollution is a pressing environmental and public health issue, contributing to a wide range of common diseases worldwide[1]. Among the most harmful pollutants are particulate matter (PM), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). Exposure to these pollutants has been linked to respiratory and cardiovascular diseases, neurological disorders, and various forms of cancer[2]. As industrialization continues to advance, understanding and mitigating the health impacts of air pollution has become more critical than ever. In recent years, the health effects modeling of air pollution has gained increasing attention, as its findings can significantly influence government policy decisions. Therefore, it is essential for researchers to conduct such evaluations with great care and precision[3]. Traditionally, modeling the health effects of air pollution has relied on statistical and mechanistic approaches. While effective to some extent, these methods often depend on extensive domain knowledge and numerous assumptions, which can limit their applicability in complex, high-dimensional data environments.

Meanwhile, the rapid development of artificial intelligence (AI) technologies is transforming numerous fields. In particular, large-scale multimodal AI systems have made remarkable progress, demonstrating superior performance in pattern recognition, information processing, and data-driven inference - even surpassing human capabilities in some areas[4-6]. Consequently, AI offers promising potential for enhancing environmental assessments and improving traditional health effects modeling. The advent of AI, especially through large-scale multimodal models, presents novel solutions to the limitations of conventional methods. AI's capacity to process large, heterogeneous datasets, identify hidden patterns, and improve predictive accuracy makes it a powerful tool for advancing research on the health effects of air pollution[7-9].

This paper delves into the application of AI in modeling the health effects of air pollution, focusing on key areas such as real-time monitoring of human and environmental conditions, integration of multimodal data, predictive modeling of health outcomes, intelligent information processing, personalized risk assessment, and decision support for public health and policy interventions, as shown in Figure 1. Additionally, it discusses the potential of adopting AI techniques from computer science and mechanical systems, such as large model training and sensor network design, for use in environmental science.

ACCURATE EXPOSURE ASSESSMENT THROUGH REAL-TIME MONITORING SYSTEM BASED ON SENSOR NETWORKS

AI-powered systems can facilitate real-time monitoring of human exposure and environmental conditions, enabling fast public health responses[10]. To assess environmental conditions, Internet of Things (IoT) sensors can be deployed in various indoor and outdoor settings across villages, towns, and cities. These sensors detect PM, NO_2, SO_2, CO, and other pollutants. Additional devices, such as cameras (including satellite imagery when available) and sensors for humidity and wind speed, can also be integrated into the system. The multimodal data collected through the IoT sensor network is transmitted to local environmental data centers for analysis. Che *et al.* developed an innovative mobile application powered by the Personalized Real-Time Air Quality Informatics System for Exposure - Hong Kong (PRAISE-HK), which supports individuals in managing and reducing personal exposure to air pollutants[11]. PRAISE-HK integrates cutting-edge sensor technologies, big data analytics, air quality modeling, and exposure science to analyze and forecast air quality at the street level in Hong Kong. Through the PRAISE-HK mobile app, users gain real-time, location-specific information about air pollution in their immediate surroundings. At the individual level, the app enables users - especially those with chronic illnesses or respiratory conditions - to make informed decisions, such as selecting cleaner routes or scheduling outdoor activities during periods of lower pollution. At the community level, the system helps identify pollution hotspots, empowering citizens to advocate for policy changes (e.g., relocating bus stops or adjusting loading times and locations) that reduce exposure for vulnerable populations. However, the current system does not sufficiently incorporate human physiological data, which is critical for assessing health status and the effects of air

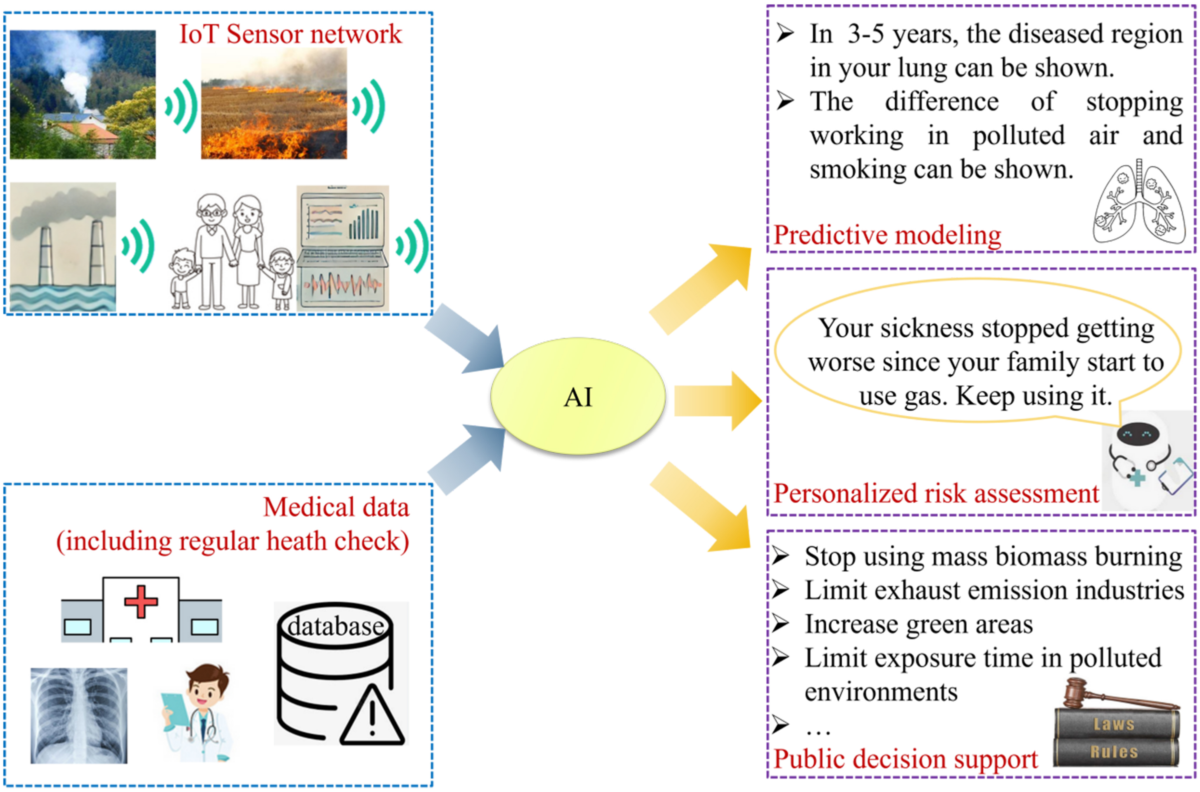

Figure 1. Overview of how AI addresses air pollution challenges: from data collection via sensor networks and medical databases to model training (predictive modeling) for risk prediction (targeting specific populations and enabling personalized assessments) and strategic decision making (supporting governmental policies). AI: Artificial intelligence.

pollution. To address this, further development is needed to enhance the system's capabilities. IoT sensors can be installed in private residences or gardens to monitor physiological indicators such as body temperature, blood pressure, and heart rate. Cameras with infrared capabilities may optionally be used to capture behavioral cues (e.g., falls or labored breathing) for special feedback scenarios. Time-series data collected from these sources can be analyzed using recurrent neural networks (RNNs) and long short-term memory (LSTM) models to support real-time predictions of both air quality and human health status[12]. Furthermore, the system could deliver real-time alerts in emergency situations, such as fires, CO leaks, toxic gas exposures, or acute medical incidents.

Ensuring the robustness and reliability of AI-powered sensor networks in real-world applications remains a major challenge. The deployment of sensors can be scaled gradually based on budgetary constraints and privacy considerations.

INTEGRATION OF MULTIMODAL AIR POLLUTION DATA

AI has demonstrated strong capabilities in integrating multimodal data, including satellite imagery, environmental sensor data, and electronic health records. Multimodal data refer to information collected from different domains or perspectives about the same object or phenomenon, where each domain or perspective is referred to as a modality. For example, convolutional neural networks (CNNs) can be used to analyze sensor data to estimate pollutant concentrations[13]. These estimates can then be linked to health outcomes by analyzing corresponding electronic health records. In addition, health check-up data, medication usage records, and disease incidence rates can be leveraged to evaluate the long-term health impacts of air pollution. According to the National Health Commission of the People's Republic of China[14], routine health check-ups have become widespread across cities, towns, and rural villages. The regular health data collected at health centers can reveal gradual changes in population health. Meanwhile, disease incidence data recorded by hospitals can provide a snapshot of the community's current health status. For instance, Shin *et al.* investigated differences in hospitalization and mortality risks associated with short-term exposure to ozone and $PM_{2.5}$, and examined whether these risks vary by season, age, or sex[1]. In the future, data on medication purchases from pharmacies and hospitals may offer real-time insights into community health, as some individuals may choose to self-medicate without seeking hospital care. By integrating all these multimodal data sources, the health impacts of air pollution can be more accurately modeled, especially for real-time health assessments, despite differences in the format, scale, or temporal resolution of the data.

However, challenges remain, including ensuring data interoperability and addressing privacy concerns. Developing standardized data-sharing protocols and privacy-preserving AI techniques will be essential to overcoming these barriers.

AIR QUALITY AND HEALTH EFFECTS PREDICTIVE MODELING

A Large Health Assessment Model (LHAM) will be developed in the future to estimate public health effects based on air quality across different regions. This more powerful assessment model will enable the prediction of morbidity and mortality associated with air quality-related diseases under current conditions. It will also enable simulation of potential results resulting from interventions, such as reducing or eliminating specific pollutants.

Deep learning models have shown good performance in predicting health effects linked to exposure to pollutants such as $PM_{2.5}$ and NO_2[15,16], as they can process data with multiple modalities and automatically capture complex, nonlinear relationships. RNNs, such as LSTM models, are particularly well-suited for predictive modeling involving time series data - appropriate for air pollution health effects, which often accumulate over time. Using widely available large-scale datasets, these models can achieve high predictive accuracy. Moreover, deep learning models can uncover hidden features - previously unknown variables that may impact human health. The influence of each feature can be assessed both qualitatively and quantitatively. For example, the residual BiLSTM model[17], a type of RNN that integrates residual networks (ResNet) with bidirectional LSTM (BiLSTM) layers, is designed to process sequential data while improving model performance and stability. Through bidirectional processing, it can extract contextual information from both the past and future directions in a sequence, enabling more comprehensive feature representation.

Despite the advantages offered by AI, challenges remain, particularly regarding model interpretability and the need for high-quality training data. Future research should prioritize the development of explainable LHAMs to improve transparency, trust, and applicability in health-related decision making.

INTELLIGENT INFORMATION PROCESSING

Current methods for evaluating health effects through controlled experiments often rely heavily on human experience and visual observation. For instance, researchers may observe changes in PM or human cells under a microscope, or manually record the formation and progression of small patterns such as cracks. However, such patterns can be difficult to identify, and tracking their number and variation can be challenging and error-prone. Machine learning-based pattern recognition techniques have demonstrated strong performance in analyzing such complex data. Some AI models have already been applied to disease diagnosis. With their high recognition accuracy and automated statistical capabilities, AI can significantly accelerate various types of health effect assessments. Additionally, AI can identify previously unnoticed patterns in observational data - potentially revealing hidden features. Generative AI also offers the ability to predict trends in health effects under different conditions. For example, large language models can simulate the progression of oxidative stress in lung cells due to long-term exposure to polluted air. An example is shown in Figure 2, which illustrates the differences between normal lung cells and those affected by various pollutants. It is important to note that these generated images are useful only for preliminary predictions or hypothesis generation in the absence of reference data. They may carry a significant risk of error or produce entirely incorrect results. As such, these images are not currently suitable for medical diagnosis or as scientific evidence. Since general-purpose AI models are typically trained on non-specialized data, their predictive accuracy in medical contexts remains low. However, a Health Effect Assessment AI Model could be specifically trained on medical diagnostic image databases, which would substantially enhance its accuracy for this specialized application.

PERSONALIZED RISK ASSESSMENT

Personalized risk assessment involves quantifying individual health risks by analyzing personal exposure and susceptibility factors. Historically, researchers have sought to predict air pollution levels by integrating data from environmental monitoring stations with urban lifestyle patterns, and subsequently recommending optimized mobility routes to reduce exposure risks for the general population[11]. However, the health impacts of air pollution vary significantly between individuals. This variability arises from differences in health status, lifestyle, allergen sensitivities, and exposure history, highlighting the need to personalize daily activity planning based on real-time physiological and biometric response data.

AI-driven analytical frameworks can integrate multidimensional datasets, encompassing genetic profiles, lifestyle habits, medical histories, and real-time physiological indicators, alongside conventional exposure metrics such as intensity, duration, and frequency. These models continuously update risk evaluations as new data are collected, enabling the delivery of individualized alerts - even among people sharing the same environmental conditions but exhibiting distinct risk profiles.

In this novel personalized risk assessment model, conventional air quality and exposure data in the user’s surroundings are combined with their medical history, underlying health conditions, and real-time biological data (e.g., blood pressure, heart rate, and body temperature). The model assesses the user’s risk level and can guide behavior by issuing warnings about potential health risks, offering activity-specific health recommendations, and providing medical suggestions for subsequent actions.

DECISION SUPPORT FOR PUBLIC HEALTH AND POLICY INTERVENTIONS

AI has been increasingly applied to support decision making in air quality management and public health interventions. For example, by analyzing patterns in emission data, AI models can perform much finer source apportionment than traditional methods[18], enabling the identification of industrial violators, traffic hotspots, and even illegal burning activities. Governments can then implement targeted interventions, such as dynamic congestion pricing, smart industrial regulations based on real-time emissions, and predictive alerts for high-risk pollution days. In this way, AI can help identify the most effective pollution control strategies and simulate the health impacts of various policy options.

With accurate exposure assessments enabled by real-time monitoring systems based on sensor networks and the integration of multimodal air pollution data, more powerful models, such as LHAM, can be trained. These models can estimate the morbidity and mortality associated with pollution-related diseases from a

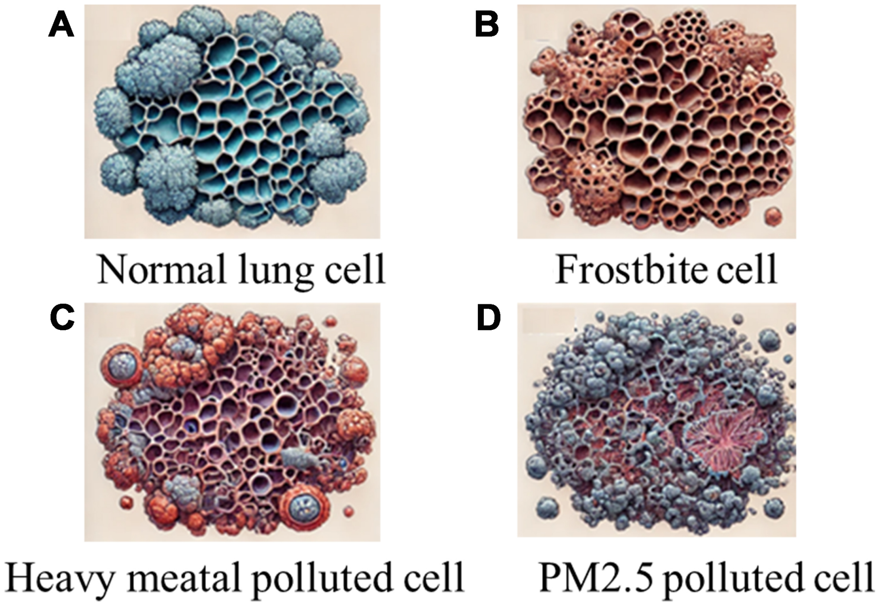

Figure 2. Simulated lung cell states under air pollution conditions. Comparison between normal lung cells and those exposed to different pollutants. Images were generated using large language models (ChatGPT). These are intended only for preliminary predictions in the absence of reference data and may carry a high risk of significant errors or incorrect predictions.

macro-level perspective. Additionally, simulations can evaluate behavioral or policy changes, such as encouraging vehicles to avoid rush hours, to identify the most effective and feasible interventions for protecting public health without harming pollution-related industries. From a micro-level perspective, communities, families, and even individuals can receive personalized risk assessments. These reports can help people adopt tailored protective measures and offer informed suggestions to policymakers.

However, challenges remain, including the need to ensure transparency and accountability in AI-driven decision making. Developing participatory frameworks that incorporate public input into AI model design and implementation will be necessary.

Limitations of AI

Although AI offers powerful tools for exposure and health assessment, several limitations must be acknowledged. These include a lack of domain-specific knowledge in the field of health assessment, a strong dependence on the quality of underlying databases, challenges in model explainability and transparency, concerns around privacy and informed consent in real-time monitoring, and limited applicability in low-resource or highly variable environments.

Ethics of AI

Data generated by AI, whether in the form of text or diagrams, should be used only for preliminary assumptions and must be strictly regulated when applied in medical or scientific contexts. Additionally, privacy protection remains a major concern when using human data for training, analyzing, and predicting exposure and health outcomes through AI models.

CONCLUSION

The integration of AI into health effects modeling of air pollution holds significant research potential. Through real-time monitoring of human health and environmental conditions, multimodal data integration, predictive health modeling, intelligent information processing, personalized risk assessment, and informed decision making for public health and policy, AI can transform our understanding and management of air pollution's health impacts. However, challenges such as data quality, model interpretability, equity, and ethical concerns must be addressed. Future research should prioritize the development of large-scale environmental models capable of processing multimodal environmental and human health data. With continued efforts, AI can become a powerful tool for advancing air pollution health research and improving public health outcomes.

DECLARATIONS

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Figure 2 was generated using a large language model (ChatGPT-4).

Authors' contributions

Drafted the initial version and contributed to subsequent revisions of the perspective: Zhang, B.
Conceptualized and revised the perspective: Sun, J.

Availability of data and materials

Not applicable.

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Conflicts of interest

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Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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