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Analyzing Research on Air Quality Modeling in the Indian Setting: A Thorough Overview

Anilumar Shimpi [1] * , Dr. Ashok Datir [2] , Dr. P. M. Nawalade [3]

1. Research Scholar, Department of Environmental Science, K.R.T. Arts, B.H. Commerce, A.M. Science College, Gangapur Road, Nashik, Maharashtra, India
anilkumarshimpi@yahoo.com ,
2. Associate Professor , Agasti Arts, Commerce & Dadasaheb Rupwate Science College Akole, Maharashtra, India ,
3. Associate Professor K.R.T Arts, B.H. Commerec and A.M Science College, Shivajinagar GANGAPUR Road, Nashik, Maharashtra, India

Abstract: India, being a developing nation, need efficient strategies to mitigate air pollution in order to prevent premature deaths of numerous individuals. Air quality models not only give data on the concentrations of air pollution, but also offer valuable knowledge about its sources. Prior research on air quality modelling conducted in India at the local and regional levels. This present study aims to evaluate the comprehensive grasp of the existing gaps and to explore potential future possibilities. The meticulously recorded studies conducted in various regions of India during the previous decade, employing systematic searches on various databases like Google Scholar and Google. The majority of air quality research mostly centers on megacities, disregarding the smaller cities that also require substantial attention in the future. There were very few research that were primarily focused on the central area of India, even though the majority of modelling studies were conducted in that region. Upon reviewing both local and regional numerical models, it became evident that there is a requirement for improved emission inputs. Furthermore, the statistical models have shown that it is important to meticulously choose key indicators in order to achieve precise source identification. Regardless of the emission inventory and models employed, Delhi consistently has significant underestimation of particulate matter concentrations, exacerbating its severe air pollution problems. The primary contributors to particulate matter in India are dust and emissions from transportation.

Keywords: Air quality Modeling, Analysis, Indian Setting, Research

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INTRODUCTION

Air is among the most vital natural resources necessary for the continued existence and survival of life on Earth. All life forms, including plants and animals are fundamentally dependent on oxygen for survival. Hence, in order to sustain existence, all organisms require air of high quality that is devoid of detrimental gases. Population growth, automobiles, and industry are driving air pollution at alarming rates[1]. Air pollution disproportionately impacts the elderly and small children. Air pollution emits acid rain, harming plants, soils, rivers, and animals. Environmental impacts of air pollution include haze, eutrophication, and global climate change. Numerous researchers have devoted considerable effort over the past few decades to the investigation and development of various models and methods for assessing and analyzing air quality[2]. Both natural and man-made elements are contributing to the difficulties that are being experienced by air, which is an essential component for the continuation of life on Earth. There has been a general reduction in air quality all across the world as a result of a number of factors, including industrialization, volcanic eruptions, forest fires and agricultural burning[3]. The creation and implementation of efficient models for air quality contribute to the integration of our understanding of the physical and chemical processes that are responsible for the emission of pollutants into the atmosphere, and they offer significant scientific support for the formulation of public policy[4].

Impact of Industrialization and Urbanisation on Indian Air Quality Modelling

The term "air quality modelling" refers to the process of estimating the amounts of contaminants in the air via the utilisation of mathematical and computer programmes. Air quality modelling is a method that has been certified by the Environmental Protection Agency (EPA) for analysing the consequences that air emission sources like industries and highways have on the quality of the air to which people are exposed[5]. The fast industrialization, urbanization, and rise in automobile traffic that have occurred as a result of significant population growth over the course of several decades have contributed to a decline in the quality of the air. In addition, the fact that environmental restrictions are not being strictly enforced has only served to exacerbate the pollution problems that are prevalent in emerging nations such as India[6]. In 2016, the World Health Organisation (WHO) reported that more than half of the top 20 cities with the worst levels of pollution were located in India. A total of 591 monitoring stations are dispersed across the country, comprising 248 municipalities and localities in 28 states and 5 union territories. These stations are operated by the Control Board (CPCB)[7]. As an illustration, during the year 2015, the mean levels of sulphur dioxide and nitrogen dioxide in the principal cities of India failed to exceed the National Ambient Air Quality Standards (NAAQS) in any of the major cities situated throughout the nation[8].

Conversely, the annual mean PM2.5 concentration in prominent urban areas spanning the northern, eastern, western, and southern regions of India exceeded the National Ambient Air Quality Standards (NAAQS) threshold of 40 µg/m by 3.3, 3.7, 2.3, and 1.6 times, respectively. Despite the passage of eight hours, the levels of carbon monoxide and oxygen in significant urban areas of northern India (47.8 and 1.26 mg/m3), eastern India (48.1 and 1.73 mg/m3), western India, and southern India remained below the thresholds set by the National Ambient Air Quality Standards (100 and 2 mg/m3)[9].

It is largely possible to relate the exceeding of pollutant concentrations to dust emissions, emissions from vehicles, the burning of biomass, and other similar activities. Intense concentrations of pollutants that meet certain conditions represent a persistent risk to both human health and the environment[10]. In 2015, India was responsible for 25.7% of all premature deaths that occurred throughout the world as a result of exposure to PM2.5. The Indian capital had a 6.5% rise in mortality rates due to PM2.5 concentrations that were higher than the WHO's recommended levels[11]. A significant number of nations with high and middle incomes has a comprehensive system of monitoring stations that span across both rural and urban regions. It is not economically possible to put up a network of monitoring stations in developing nations like India[12]. In India, where air pollution is among the worst in the world, it is vital to check the pollution levels constantly. Furthermore, the limited distribution of monitoring stations restricts their use, necessitating the adoption of air quality models to get comprehensive information on the geographical and temporal fluctuations of pollutant levels[13].

Local and Regional Air Quality Modelling on Air Pollution Assessment

By using source studies that make use of source-oriented regional air quality models, the sources' Contributions can be gathered independently of observation frequency and geographic coverage[14].

Based on geographical resolution, air quality models may be categorised as:

(i) **Local models:** Local/urban scale models are those in which the domain size varies between a few metres and several kilometres.

(ii) **Regional models:** Regional models are those that inhabit an area spanning from tens to hundreds of kilometres in domain length.

(iii) **Global/meso scale models:** Models categorised as global/meso scale models are those that lack the level of refinement as regional models.

At the local/urban level, a sensitivity analysis was carried out using a regional photochemical model of ozone, and the results showed a correlation between rising local/urban ozone levels and rising regional ozone levels[15]. Hence, the emission of pollutants in a specific area might have an impact on the overall air quality of the surrounding region[16]. Detailed information on the current state of air quality in our immediate neighborhood may be obtained through the use of local air quality modelling studies. A three-dimensional Eulerian model based on vehicle emissions was used to simulate the dispersion of gaseous air contaminants close to highways[17]. Researchers computed the source contributions of volatile organic chemical fluxes in a city using a receptor model. The spatial coverage of regional models is higher, and they are able to assist in the prediction of concentrations or the identification of sources since they pertain to a much wider scale[18]. Validation of emission inventories of contaminants is frequently accomplished through the use of these studies. Emissions from houses and enterprises were found to be the dominant sources of primary PM2.5, according to the findings of a source study of particulate matter in China that utilised a source-oriented air quality model[19].

However, major sources of secondary aerosols were transportation, power plants, industry, and agriculture. A great number of research on modelling air quality have been conducted in the past, all over the world, at both the local and regional scales, for a variety of tasks[20]. To acquire a better knowledge of the performance of the model, it is essential to combine and assess the findings that were obtained from the experiments that were conducted on various scales. Air quality can currently not be successfully predicted at all geographical scales using a single model, with emissions having the highest level of uncertainty among inputs[21]. This was discovered through an analysis of modelling techniques in the European Union (EU). The review of ozone modelling studies from around the world revealed that there is an overestimation of nighttime ground level ozone (GLO), an increased contribution from temperature rise and biogenic volatile organic compounds to the concentration of greenhouse gases in the atmosphere, as well as a greater influence of nitrogen oxides (NOx) over volatile organic compounds (VOCs) in the export of ozone from urban zones[22].

Modeling and Forecasting of Air Quality

Air quality modelling and forecasting serve the purpose of meeting the requirements of both individuals and government agencies to understand the past and future changes in the surrounding air quality at a particular location within a defined time frame[23]. Individuals, particularly those who are susceptible to heart or respiratory conditions, may require information on the projected air quality index in order to make informed decisions about engaging in outdoor activities on days with poor air quality[24]. The government agencies responsible for distributing this public information are required to build an air quality forecasting system that anticipates the changes in concentrations of criterion air pollutants over the following 24 hours or beyond[25].

There are two primary techniques for developing the air quality forecasting system:

- **Statistical modelling technique:** Using this method, the concentration of contaminants is predicted by using an empirical model or a mixture of models. The forecast is based on past pollutant concentrations, precursor concentrations, and other important climatic variables that may have an impact on the pollutant's dispersal, mobility, and removal.
- **Chemical transport modelling technique:** The chemical transport model is a three-dimensional air quality model that uses both Eulerian and Lagrangian approaches to simulate pollutant concentrations. It calculates the concentration of pollutants either for a specific area within the model domain or for individual air parcels.

However, other models such as multiple linear regression, classification and regression tree, and multilayer perceptron are also utilised in conventional statistical models to forecast ambient air quality levels of pollutants like PM2.5 and other gaseous pollutants (artificial neural network). Using a linear combination of the input variables, multiple linear regression predicts the concentration of pollutants[26]. The input space is recursively partitioned by the classification and regression tree technique, enabling each division to use its own models for example, several linear regression models with different coefficients. The multilayer perceptron is a feed forward artificial neural network that uses a linear combination of hidden neuron outputs to forecast the concentration of pollutants[27].

The expected air pollutant concentration in a statistical air quality forecasting model can be associated with a wide range of possible meteorological data. However, it may produce erroneous predictions when applied to unknown data during the validation process[28]. Forecasters must determine the optimal mix during the process of model construction. In addition to that, another obstacle is typically encountered even when the input variables are methodically chosen, meaning that the models are nonadaptive[29]. Throughout operational forecasting, the model parameters which are obtained from a predetermined set of training data will not change. Forecast error may result from the model coefficients gradually changing during operational forecasting[30].

Photochemical Air Quality Modeling Research

In recent years, photochemical air quality models have garnered a lot of attention and are now often used as instruments for regulatory analysis and attainment demonstrations[31]. For the purpose of determining which aspects of control procedures are in need of enhancement, these models do an evaluation of their effectiveness. In order to depict the physical and chemical phenomena occurring in the atmosphere, these photochemical models function as expansive air quality simulations through the application of a collection of mathematical equations. These models effectively simulate and reproduce the variations in pollutant concentrations in the atmosphere. A variety of geographic dimensions are utilised in the implementation of these models, including local, regional, national, and international[32].

Some examples of photochemical models are the following:

- **Community Multiscale Air Quality Model:** The primary aim of the Models-3/Community Multiscale Air Quality (CMAQ) modelling system is to enhance the environmental management community's capability to assess the impacts of different pollutants' air quality management strategies across different scales. The other primary objective is to enhance the understanding, ability to simulate, and investigation of chemical and physical interactions in the atmosphere among scientists[33].

- **Comprehensive Air quality Model:** A computer modelling system that is open-source and accessible to the general public is known as Comprehensive Air Quality Model with Extensions. It is designed for the purpose of conducting an integrated evaluation of gaseous and particle atmospheric pollution. Built on the current awareness that problems with air quality are multifaceted, interconnected, and extend beyond the geographical boundaries of metropolitan areas[34], CAMx is intended to:

- For the purpose of treating a wide range of inert and chemically active contaminants.
- To replicate various geographic scales of air quality.
- To study the inorganic and organic PM2.5/PM10, as well as mercury and hazardous substances, it is necessary to offer source-receptor, sensitivity, and process evaluations. It should be easy to use and efficient in terms of computing.

- **Urban Air Quality Model:** Systems Applications International (SAI) is responsible for the development and maintenance of the Urban Air Quality Model system, which is now the photochemical air quality model that is utilised the most often all over the world. Following the groundbreaking work that SAI undertook in the field of photochemical air quality modelling in the early 1970s, Application, performance evaluation, update, extension, and improvement cycles have been applied to the model in a manner that is nearly continuous[35]. These cycles have been carried out several times. During this extended period of time, a number of other photochemical models have been created; nonetheless, there is currently no model that is more dependable or technically superior[36]. Photochemical grid models attempt to realistically portray air pollution formation, accumulation, and dissipation. They simulate the key ozone-generating mechanisms. To correctly characterise city winds that transport pollution, photochemical grid models are driven by meteorological models like those used for weather forecasting[37]. Industrial sources, vehicles and trucks, locomotives, ships, and many more sources produce chemicals that generate ozone. Third, photochemical grid models replicate ozone-forming photochemical processes. Sunlight triggers "photochemical" processes, which can produce highly reactive "radicals" molecular fragments[38]. Ozone is formed when these radicals combine with volatile organic molecules and nitrogen oxides[39].

Components of Air Quality Model

Each and every air quality modelling system is comprised of three primary components, which, when utilised in conjunction with one another, contribute to the process of identifying and forecasting the environmental destiny of air pollutants following their emission. The components in question are as follows: (1) emissions; (2) meteorological; and (3) air quality conditions. The passage of time has an impact on each of the three components of air modelling[40]. The components of the emissions inventory that are considered to be the most significant include the sources of air pollutants that are released in the specific urban or regional area that is being modelled, as well as those that are adverted by mean winds from beyond the area. Because of this, it is vital to have a complete emissions inventory that includes both natural and human sources[41].

Recent developments in modelling have made it possible for users to increase their accuracy in estimating the link between sources of pollution and the effects those sources have on the quality of the air around them, to forecast the effects that may be caused by potential emission sources, and to simulate the concentrations of pollution in the air under a variety of policy scenarios. It is with their assistance that the identification of the relative contributions from the various sources, the monitoring of compliance with the regulations governing air quality, and the formation of policy options are all done[42]. The development of multimedia and multi-stressor models to handle complex environmental concerns is another aspect of this study that is contributing to the enhancement of the capability to undertake multipollutant air quality evaluations at local, regional, national, and global scales.

Thus, the essential elements of air quality modelling are as follows:

- An understanding of sources and static data.
- Parameterization, diffusion, and transport.
- Chemical processes of change.
- The removal method.
- Meteorological observations.
- Concenteration/Deposition.

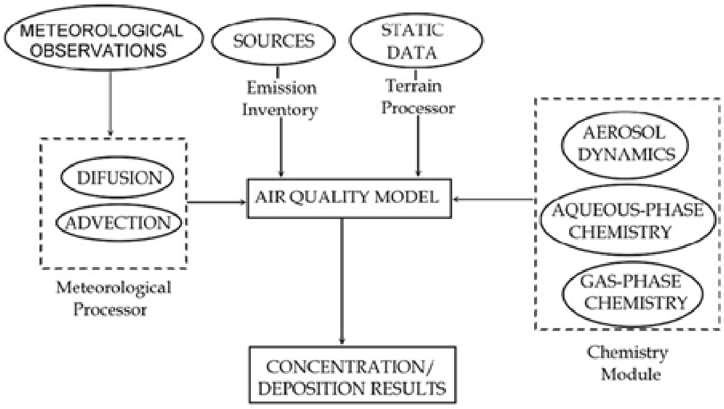

Figure 1: Components of Air Quality Model

(Source: Goyal et al., 2010)

Certain pollutant concentrations in urban areas, such as particulate matter and O3, are significantly impacted by long-range pollutant transport. On the other hand, certain atmospheric chemical processes that result in episodes of regional air pollution are significantly influenced by anthropogenic emissions originating from industrial and urban regions[43]. Pore and particulate matter concentrations in rural areas are impacted by volatile organic compound (VOC) and NOX emissions, respectively. Studies on population exposure require systems that couple regional and local air quality models for the purpose of quantifying baseline air pollutant concentration. These nested models may also be used to evaluate the probable consequences of proposed national and local pollution mitigation strategies. Incorporating the entire spectrum of spatial scales into population exposure studies is necessary[44].

Air Quality Evaluation

An essential method for monitoring and regulating air pollution is air quality evaluation assessment. Evaluations of air quality have been carried out using traditional methods for the past several decades[45]. The suitability of an air supply for a particular purpose is determined by its characteristics. Certain air pollutants, referred to as criteria air pollutants are ubiquitous. These pollutants have the potential to cause property damage, environmental injury, and health hazards. Currently, the following pollutants meet the criteria: 1) Carbon Monoxide, (2) Lead, 3) Nitrogen Dioxide, 4) Ozone, 5) Particulate Matter and 6) Sulphur Dioxide. The Air Quality System (AQS) comprises ambient air pollution data gathered from thousands of monitors by EPA, state, local, and tribal air pollution control agencies[46].

The Air Quality Monitoring System (AQS) includes not only meteorological data but also descriptive information on each monitoring station, such as its operator and geographic location, as well as specifics regarding data quality assurance and control[47]. Other air quality management functions include the evaluation of State Implementation Plans for Non-Attainment Areas, the assessment of air quality, the modelling of permit review analysis, and the assistance with Attainment/Non-Attainment designations[48]. The oversight of programmes implemented by the Environmental Protection Agency (EPA) to mitigate air pollution in regions where the current standard is unsatisfactory and to prevent degradation in areas with relatively clean air is the responsibility of the Office of Air Quality Planning and Standards (OAQPS). In order to achieve this objective, the National Ambient Air Quality Standard (NAAQS) is established by OAQPS for every criterion pollutant.

Primary and secondary standards are the two categories of standards:

1) Primary standards: safeguard against detrimental health consequences;

2) Secondary standards: provide protection against welfare impacts, including structural and agricultural crop and vegetation damage. Due to the fact that various pollutants elicit distinct impacts, the NAAQS standards also vary. Both short-term and long-term averaging periods are detailed in the standards for certain contaminants. At the same time as short-term standards are meant to give protection against acute or short-term health consequences, long-term standards were created with the purpose of providing protection against ongoing health problems. Standards for both short-term and long-term averaging times exist for certain pollutants. The primary objective of short-term standards is to mitigate acute or transient health consequences. In contrast, long-term standards are in place to safeguard against chronic health effects.

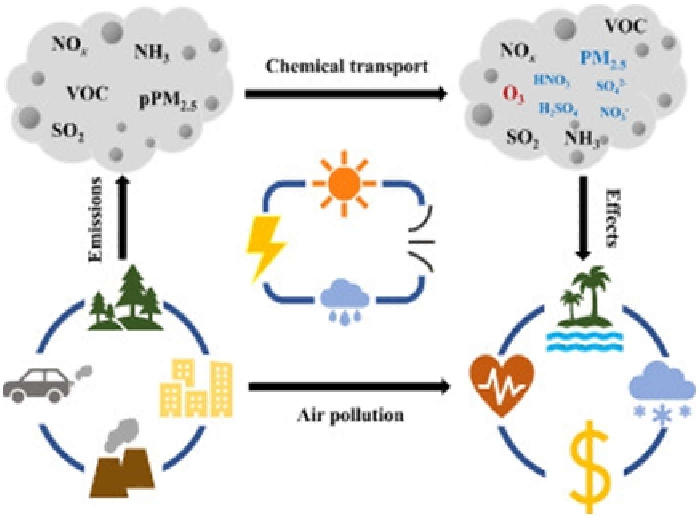

Figure 2: Monitoring of Air Quality

(Source: Behera et al., 2011)

Despite the progressive development and intricacy of these models, their application to real-time atmospheric pollution monitoring appears to be inadequate due to concerns regarding performance, input data prerequisites, and adherence to time constraints. As an alternative, offline investigations of the phenomena at hand have relied primarily on mathematical models, whereas Air Quality Operational Centers have predominantly utilised the knowledge of human experts to make real-time decisions[49]. Physical reality has been utilised as the foundation for measuring air pollution phenomena. There is a positive correlation between the AQI and the proportion of the population that is exposed to hazardous substances, which may result in progressively severe health consequences[50]. An individual air quality index is utilised in each country, which corresponds to a unique set of national air quality standards. High levels of nonhomogeneity are seen in anthropogenic pollution emissions, particularly aerosol concentrations[51]. In terms of the concentration of particles and precursors, as well as the gas-phase chemistry, the reactions that take place during the synthesis and transition of aerosols are highly nonlinear. In every single one of these three aspects, this is consistently the case[52]. It has been discovered that the scale at which the processes of emissions, creation, and transformation are resolved in models has a considerable influence on the concentration fields of the aerosols and gas-phase compounds that are created as a result of these activities' occurrence[53]. This is because the scale at which these processes are resolved has a substantial impact[54].

Sustainable development goals of Air Pollution

The Sustainable Development Scenario (SDS) is an initiative that expands upon the chosen United Nations Sustainable Development Goals (SDGs). The primary aim of this initiative is to create a structural framework that integrates three distinct yet interconnected policy goals: firstly, ensure that all individuals have access to affordable, reliable, and modern energy services by the year 2030; secondly, substantially reduce the adverse health impacts of air pollution; and thirdly, execute effective strategies to address climate change. The Sustainable Development Goals (SDGs) are a compilation of seventeen objectives and one hundred ninety-nine targets, as declared by the United Nations. All Member States ratified these objectives and goals in 2015 as an integral component of the 2030 Agenda for Sustainable Development. They address global challenges in addition to issues including poverty, inequality, economic development, climate change, environmental degradation, and justice. The World Health Organization (WHO) has made efforts to ensure that the official system of Sustainable Development Goals (SDG) indicators take into account health-related indicators such as exposure to household and ambient pollution and the burden of illness.

In the context of air quality, the Sustainable Development Goals (SDS) do not seek to meet any particular universal pollutant exposure objectives throughout the projection period of 2020-2040. As an alternative, the scenario proposes a combination of actions in order to achieve the greatest possible reduction in air pollutants. In order to accomplish this goal, the scenario assumes the maximum possible application rates for abatement technology and regulatory approaches for the reduction of pollutant emissions. Additionally, it presupposes that policy signals are sufficiently powerful and synchronized to guarantee that decisions regarding energy investment take into consideration both air pollution and climate goals simultaneously. This is done in order to prevent unintended lock-in effects and to lower the total costs of compliance[55].

- **Correlation between air quality and the UN Sustainable Development Goals**

The Sustainable Development Goals of the United Nations serve as a strategic guide for attaining an improved future for both humanity and the environment. Three Sustainable Development Goals (SDGs) encompass air quality and air pollution. First is Goal 3 i.e. “Good Health and Well-Being” address that by 2030 the amount of hazardous chemical-related fatalities, diseases as well as soil, water, and air pollution and contamination by a significant margin will be reduced. Similarly, Goal 11 i.e. “Sustainable Towns and Cities” implies that the negative environmental effects of cities per person, especially by focusing on air quality and managing municipal and other garbage will be reduced by 2030. Furthermore, according to

Goal 12 (Responsible Consumption and Production), all chemicals and wastes should be managed sustainably throughout their lifecycle, in compliance with internationally recognized frameworks by 2020. Their release into the air, water, and soil should be drastically reduced to minimize any negative effects on the environment and public health.

In addition to these consequences, additional SDGs pertaining to clean water, conservation, and industrial innovation are also related to the climatic and socioeconomic effect of air pollution[56].

CONCLUSION

An exhaustive evaluation that takes into account both regional and local air quality modelling studies has not yet been carried out in India. This is an essential component in the process of effectively formulating policies to reduce air quality impacts. Almost little local or regional studies are carried out in the central area of India. Furthermore, more research is focused in northern India because of the larger densities in the Indo Gangetic plain. For instance, data from 75% of RSA, research come from northern and eastern India. Compared with VOCs and PAHs, which are extremely carcinogenic and require more care, there are many RSA research on PM. The point of uncertainty in RSA research is caused by inconsistent source tracer selection. Differential sources in different parts of India result in PM with varying spatiotemporal, physical, and chemical properties. In the northern area, industrial and transportation emissions are the two main sources of emissions in Kanpur and Agra, whereas dust emissions are the main source in Delhi. In southern and eastern Indian cities, coal combustion is often cited as the primary cause, followed by traffic and dust emissions. It is important to acknowledge that the preponderance of regional studies project PM concentrations in Delhi, irrespective of the emission inventory or the model employed, to be below average. In contrast, the identical model configuration is doing admirably in other places. The present emission inventory might be modified based on the findings of the local RSA investigations, which is one strategy that could be taken to address the issue.

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