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REVIEW

Efficiency Evaluation and Path Optimization of Regional Atmospheric Environment Governance from a Synergistic Emission Reduction Perspective Synergistic Control of $PM_{2.5}$ and O_3

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ABSTRACT

There is a growing challenge posed by the coexistence of fine particulate matter ($PM_{2.5}$) and ground-level ozone (O_3). Despite the significant reductions in primary particles and a variety of gaseous pollutants achieved by conventional air pollution control, O_3 pollution has remained or even increased in many areas, demonstrating the shortcomings of single-pollutant regulation. This review examines how the efficiency evaluation and path optimization of regional atmospheric governance can be viewed through the prism of synergistic emission reduction to coordinate control of $PM_{2.5}$ and O_3. It initially explains the chemical linkage between $PM_{2.5}$ and O_3 through common precursors, the atmosphere's capacity for oxidation, photolysis, heterogeneous reactions, and regional transport. It subsequently discusses efficiency evaluation methods, such as indicator systems, data envelopment analysis, slack-based measure models, Malmquist indices, spatial econometric methods, and integrated benefit assessment. The review also discusses pathways for emission reduction across the industrial, power, transport, residential, and agricultural sectors, with a focus on differentiated VOCs-NO_x sensitivity, NH_3 regulation, structural adjustment, clean-energy transition, process optimization, and scenario-based cost-benefit analysis. Lastly, it suggests a regional path-optimization framework that combines air-quality modeling, economic analysis, cross-regional responsibility sharing, policy synergy, and adaptive, data-driven governance. The review claims that successful atmospheric governance needs to shift toward mechanism-based, regionally coordinated, and welfare-oriented decision-making to achieve sustainable air-quality improvements, health protection, carbon

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co-benefits, and regional equity.

Keywords: $PM_{2.5}$; Ozone; Synergistic Emission Reduction; Governance Efficiency; Regional Path Optimization

1. Introduction

$PM_{2.5}$ and ground-level ozone (O_3) remain two of the most significant indicators of atmospheric environmental quality in the region [1]. In most areas, particularly those experiencing rapid industrialization, urban growth, and energy-system transformation, air pollution control has entered a new phase in which reducing a single pollutant is no longer the main focus; rather, it is a coordinated mitigation of complex, compound, and regionally transported pollution. In recent decades, significant achievements have been made in reducing primary particulate emissions and conventional gaseous pollutants through measures such as industrial end-of-pipe treatment, retrofitting coal-fired power plants, vehicle emission standards, and clean energy substitution. These efforts have helped achieve significant reductions in $PM_{2.5}$ levels in most cities and regions. Nevertheless, O_3 pollution has become more pronounced, and in certain places it has even remained at the same level or even increased, despite the overall downward trend in particulate matter. This divergence implies that the existing single-pollutant governance framework is inadequate to address the nonlinear, interactive nature of the current atmospheric pollution environment [2,3].

The simultaneous presence of $PM_{2.5}$ and O_3 pollution is a testament to the complexity of atmospheric chemical processes and the structure of emissions in the region. $PM_{2.5}$ consists of both primary and secondary elements that are formed through atmospheric reactions of sulfur dioxide, nitrogen oxides, volatile organic compounds, ammonia, and other precursors. O_3, in its turn, is a secondary pollutant that is mostly produced in the process of photochemical reaction of nitrogen oxides and volatile organic compounds under the influence of solar radiation. The processes that form $PM_{2.5}$ and O_3 are not independent. Alterations in aerosol loading can affect solar radiation, photolysis rates, atmospheric oxidation capacity, and boundary layer dynamics, which in turn affect O_3 production. Likewise, when atmospheric oxidation is enhanced, the formation of secondary aerosols, such as sulfate, nitrate, and secondary organic aerosol, can be accelerated. In turn, emission reduction policies that focus on one pollutant can yield synergistic benefits and trade-offs or even unintended adverse impacts on other pollutants. By way of example, a decrease in nitrogen oxide levels might reduce the formation of nitrate aerosols, but under VOC limitation, it might also promote the formation of O_3. Similarly, a decrease in $PM_{2.5}$ can enhance atmospheric visibility and affect the formation of O_3. These interactions render the synergistic management of $PM_{2.5}$ and O_3 a key scientific and policy problem [4,5].

A further complexity in how regional atmospheric environment governance is carried out is the spatial mobility of air pollutants and their precursors. The characteristics of regional transport of $PM_{2.5}$ and O_3 pollution are often highly regional; i.e., air quality in one city is influenced not only by local emissions but also by those of neighboring cities [6]. The atmospheric circulation and economic supply chains tend to connect industrial clusters, transportation corridors, energy bases, urban agglomerations, and agricultural regions. Consequently, isolated local control measures might not be very effective due to a lack of regional coordination. Joint prevention and control, differentiated emission reduction, regional responsibility-sharing, and cross-border compensation have thus become significant elements of atmospheric governance [7]. Nevertheless, the success of these measures depends on the ability to coordinate policy instruments, emission reduction targets, industrial structures, and environmental capacities across administrative boundaries. This raises an important question: how can the efficiency of governance of atmospheric environments in the regions be measured under the mandate of synergistic $PM_{2.5}$ and O_3 control, and how can optimal emission-reduction pathways be designed to maximize environmental, economic, health, and social benefits?

The available literature has provided useful information on air pollution control, the development of emission inventories, atmospheric chemical processes, the assessment of health risks, and policy analysis. The governance of $PM_{2.5}$ has frequently centered on the apportionment of sources, the reduction of concentrations, the restructuring of industries, and health benefits [8]. Research on O_3 pollution has focused on photochemical sensitivity, VOCs-NO control regime, precursor reduction, and meteorological effects [9]. In the meantime, efficiency evaluation studies have employed methods such as data envelopment analysis, stochastic frontier analysis, slack-based measure models, Malmquist productivity indices, and spatial econometric analyses to measure environmental governance performance. Moreover, air quality models and scenario simulations have been used extensively to estimate the effects of other emission-reduction options. Though these streams of research are well developed, they are usually fragmented. Most studies assess the efficiency of atmospheric governance using aggregate pollution indicators without fully accounting for the chemical relationship between $PM_{2.5}$ and O_3. Others examine synergistic emission-reduction mechanisms but pay little attention to the efficiency of governance, resource allocation, and path optimization. As a result, atmospheric science, environmental economics, and regional policy optimization still lack connections to one another.

The novelty of this review is that it seeks to integrate synergistic emission reduction, efficiency evaluation, and regional path optimization into a single analytical model [10]. First, unlike traditional reviews that treat $PM_{2.5}$ control and O_3 mitigation separately, this article takes a coordinated control of $PM_{2.5}$ and O_3 as its main focus. It highlights that the governance of $PM_{2.5}$ and O_3 should not be regarded as two parallel policy agendas but rather as an integrated system influenced by precursor emissions, atmospheric oxidation capacity, meteorological factors, regional transport, and socioeconomic activities. This article sheds light on the scientific foundation of policy design that can not only avoid the effects of pollutant substitution but also ensure multi-pollutant co-benefits.

Second, this review presents a new core dimension of synergistic atmospheric control: governance efficiency [11]. The governance of air pollution is not just a question of whether pollutant concentrations can decrease, but also of whether environmental improvement will be achieved at a reasonable cost to the economy, with efficient use of resources, fair distribution of responsibilities across the region, and sustainable social benefits. The evaluation systems used in the past are usually centered on the end outcomes, which may include a change in concentration or emission reduction. Conversely, this article underscores the need to investigate the correlations between governance inputs and outputs, such as financial investment, energy consumption, technological innovation, administrative regulation, industrial adjustment, public health improvement, carbon reduction, and ecological benefits [12]. This point of view can be used to determine whether a region is actually attaining air-quality improvement due to efficient and sustainable governance or merely due to high-cost, short-term, or spatially transferred measures.

Third, the article develops a path-optimization view of regional atmospheric environmental governance [13]. The best emission solution (i.e., emission-reduction pathway) is unlikely to be the same across regions for $PM_{2.5}$-O_3 pollution. Regions vary in terms of industrial structure, energy mix, transport structure, meteorological conditions, and photochemical sensitivity regimes. Thus, the emission reduction strategies should be geographically distinguished and altered dynamically. In the case of VOC-limited regions, the control of reactive VOC species from industrial use of solvents, petrochemical processes, vehicle evaporation, and consumer products may need to be given priority [14]. In the case of NO_x-limited regions, joint reductions in emissions from combustion might prove more efficient. In areas affected by both local and external transport, regional actions may be required. Through the contemplation of such links, this review will attempt to provide a decision-oriented framework to underpin differentiated, cost-effective, and synergistic governance strategies.

Fourth, this paper expands the concept of synergy in pollutant control to policy coordination. Synergistic emission reduction should not be limited to the coordinated mitigation of $PM_{2.5}$ and O_3; it should also encompass integrating air pollution control and carbon neutrality, protecting public health, upgrading industry, transforming energy sources, and adapting to climate change [15]. Various measures, including renewable energy replacement, transport electrification, clean industrial processes, and urban green infrastructure, can deliver multiple environmental benefits. Some measures, however, may also involve trade-offs, such as a high demand for electricity, or a redistribution of emitted materials, or an uneven distribution of the burden. Thus, there is a need to conduct a thorough review to determine how various policy tools can enhance governance efficiency without producing fragmented or even opposing policy outcomes. The article addresses that requirement by exploring how the policies aimed at reducing emissions, regional coordination mechanisms, and multi-objective optimization models may be coupled.

The main aim of the proposed review is to provide a systematic, interdisciplinary insight into how the governance of the regional atmospheric environment can be evaluated and optimized from the perspective of synergistic control of $PM_{2.5}$ and O_3 [16]. The specific focus of the article is to explain the atmospheric processes underlying $PM_{2.5}$-O_3 interaction, summarize the current methods of assessing the efficiency of governance, compare the key emission reduction pathways across sectors and regions and propose the integrated framework of regional path optimization. The review also finds major limitations in the current research, including the failure to sufficiently consider nonlinear chemical responses, lack of sufficient integration of air-quality models and efficiency models, insufficient treatment of regional spillover effects, and inadequate assessment of co-benefits across air pollution, carbon emissions, and public health.

By addressing these concerns, this article will contribute to scientific research and to the practice of environmental policy. Scientifically, it helps narrow the gap among atmospheric chemistry, environmental management, and regional economics. On a methodological level, it provides a foundation for constructing more comprehensive evaluation systems that account for multi-pollutant interactions and multi-dimensional governance outcomes. In practice, it can inform policymakers planning differentiated, cooperative, and adaptive air pollution control strategies in areas experiencing simultaneous $PM_{2.5}$ and O_3 issues. As atmospheric governance enters the phase of deep emissions reduction, intricate interactions among pollution, high-quality development demands, and the need to integrate efficiency evaluation and path optimization will become increasingly important. A synergistic perspective is thus critical to improving air quality in the region, reducing health risks, and promoting environmental justice and sustainable development [17]. The overall conceptual framework linking emission sources, atmospheric transformation, governance efficiency evaluation, and regional path optimization is presented in **Figure 1**.

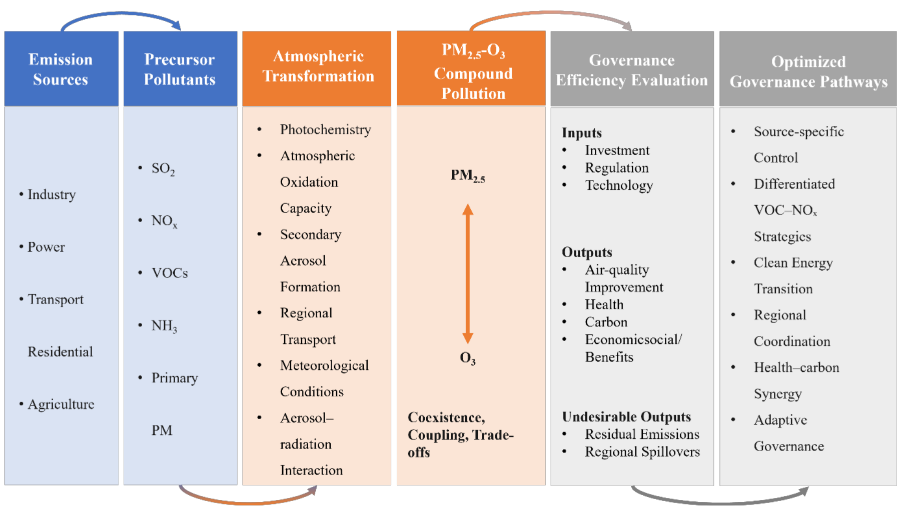

Figure 1. Conceptual framework of regional atmospheric governance from a synergistic $PM_{2.5}$ and O_3 control perspective.

2. Mechanisms and Theoretical Basis of Synergistic $PM_{2.5}$ and O_3 Control

2.1. Formation Mechanisms of $PM_{2.5}$ and O_3

Representative pollutants in regional atmospheric pollution are $PM_{2.5}$ and ground-level $_{O3}$, but their formation mechanisms differ significantly. $PM_{2.5}$ is a mixture of primary particles, which are created during combustion, industrial processes, dust, and biomass burning, and secondary particles, formed as a result of the atmospheric chemical reactions [18]. Sulfate, nitrate, and ammonium are the main inorganic aerosols generated through the oxidation of SO_2, NO_x, and NH_3, and secondary organic aerosol is formed through the oxidation of volatile organic compounds. Thus, $PM_{2.5}$ pollution is controlled not only by direct particulate emissions but also by the availability of gaseous precursors, the atmospheric capacity for oxidation, humidity, temperature, and aerosol liquid water content.

O_3 is a typical secondary photochemical pollutant. It is not emitted directly in large amounts but is produced by photochemical reactions of NO in the form of NO in the presence of VOCs under the influence of solar radiation [19]. The interaction between O_3 and its precursors is extremely nonlinear. In VOC-limited regimes, individual NO_x reductions may reduce O_3 titration, but reducing VOCs may be more effective. In the regimes of NO_x -limited, the inhibition of O_3 is generally inhibited by the reduction of NO_x. This nonlinear response complicates O_3 control compared to traditional pollutant control and necessitates region-specific diagnosis of photochemical sensitivity.

The co-occurrence of $PM_{2.5}$ and O_3 in the air suggests that control of primary emissions has shifted toward control of secondary transformations [20]. This change necessitates a greater comprehension of atmospheric chemical processes. A policy that merely leads to a decrease in overall emissions might not necessarily produce commensurate changes in air quality. Rather, the success of control efforts is determined by the composition of emissions, ratios of precursors, weather patterns, and regional transportation routes.

2.2. Chemical Coupling between $PM_{2.5}$ and O_3

While $PM_{2.5}$ and O_3 may be considered as two distinct policy targets, they are chemically and physically linked to each other. The coupling is primarily caused by the oxidation capacity of the atmosphere, the rates of the photolysis, the rates of the heterogeneous reactions and the competition of the precursors. O_3 and other oxidants (hydroxyl radicals and nitrate radicals) oxidize SO_2, NO_x, and VOCs, and increase the formation of sulfate, nitrate, and secondary organic aerosol (SOA) [21]. From this perspective, it is expected that higher photochemical activity would lead to more secondary $PM_{2.5}$ formation.

Concurrently, $PM_{2.5}$ may impact O_3 generation through radiation transfer and atmospheric chemistry changes. High aerosol loading can scatter and/or absorb solar radiation, which will decrease the rates of photolysis and surface-based photochemical O_3 production. Aerosol particles also serve as surfaces for heterogeneous chemistry, such as reactions involving radicals and the lifetime of active nitrogen species. The reduction of $PM_{2.5}$ levels is likely to lead to more photochemical reactions, thus enhancing the rise in O_3 levels under specific conditions. This phenomenon is in part why some areas have lower $PM_{2.5}$ levels, but higher and worsening levels of O_3 pollution [22].

The interaction between $PM_{2.5}$ and O_3 is not fixed but varies with season, location, meteorology, and emission structure. In winter, high humidity and stable boundary layers may favor secondary aerosol formation, while O_3 pollution is generally weaker due to limited photochemistry. In summer, strong solar radiation and high temperature promote O_3 production and secondary organic aerosol formation. Therefore, synergistic control must move beyond static emission-reduction targets and incorporate seasonal and regional differences in chemical response [23].

2.3. Role of Precursors in Synergistic Emission Reduction

Controlling $PM_{2.5}$ and O_3 fundamentally depends on controlling shared, interacting precursors, such as NO_x, VOCs, SO_2, NH_3, and primary PM. NO_x is a dual gas in the atmosphere [24]. It can act as a precursor to $PM_{2.5}$ formation via nitrate formation, and it can also be a precursor to O_3 formation in the atmosphere. But the impact of NO_x reduction on O_3 depends on the VOCs–NO_x sensitivity regime. This twofold attribute makes NO_x control a necessity while also posing a potential risk without chemical diagnosis.

VOCs play a very important role in the formation of O_3 and SOP [25]. The chemical reactivity and aerosol formation potentials of VOC species vary. Oxygenated VOCs, aromatics, and a few industrial solvent-related compounds can play a significant role in both O_3 and secondary organic aerosol formation. So, it is important to recognize that VOC control should not only focus on the overall reduction of VOC emissions, but also on the reactivity of VOC species and priorities of VOC sources. Industrial coating, production of petrochemicals, solvent use and evaporation from vehicles and fuel storage are among the main ones.

Historically, SO_2 control has played a major role in reducing $P_{2.5}$ by reducing sulfate formation [26]. However, with reduced SO_2 emissions, nitrate and organic aerosols can become more significant contributors to $PM_{2.5}$. The role of NH_3 also continues to increase due to its ability to neutralize the acidic species and promote the formation of ammonium nitrate and ammonium sulfate. Sources of NH_3 are mainly agricultural activities and livestock production, fertilizer application, and waste treatment, which tend to be less controlled than sources from industry and traffic. Weak control of NH_3 can limit further reductions in $PM_{2.5}$ and reduce the effectiveness of control over NO_x and SO_2 [27].

Therefore, a synergistic strategy for emission reduction is needed to account for the combined effects of precursor reductions. The challenge is finding reduction pathways that benefit secondary aerosol reduction and O_3 formation without causing unwanted chemical reactions.

2.4. Atmospheric Oxidation Capacity and Compound Pollution

The concept of atmospheric oxidation capacity is a key framework for understanding the relationship between $PM_{2.5}$ and O_3 [24]. It is a measure of the atmosphere's capacity to convert primary pollutants into secondary pollutants, and is mainly governed by oxidants like OH, O_3, NO_3 radicals, and hydrogen peroxide. High oxidation capacity promotes gas-to-particle conversion of gaseous precursors to secondary aerosols and boosts photochemical O_3 production. So the oxidation capacity is a chemical connection between particulate pollution and photochemical pollution.

For areas with high anthropogenic emissions high oxidation capacity can cause rapid secondary transformation, resulting in concurrent $PM_{2.5}$ and O_3 episodes. For instance, the oxidation of VOCs can result in the secondary formation of O_3 via the formation of peroxyl radicals, and additional oxidation products can lead to the formation of secondary organic aerosol [28]. Under conditions conducive for gas-particle partitioning, NO_x oxidation may be a significant pathway to nitrate aerosol formation. The gas-phase, aqueous-phase, and heterogeneous pathways are all possible mechanisms for SO_2 oxidation, and the significance of each pathway will vary with the humidity, aerosol acidity, oxidant concentration, and metal-catalyzed reactions.

An important finding is that controlling primary pollution alone may not be sufficient to control compound pollution when atmospheric oxidation strength is high. On the other hand, controlling highly reactive VOCs and NO_x can decrease O_3 and secondary $PM_{2.5}$ by slowing radical propagation and secondary transformations [29]. Hence, the capacity of the atmosphere for oxidation must be taken into account for the governance efficiency assessment and path optimization. Pollution responses can vary from regions with similar emissions due to variations in oxidation conditions, meteorology, and aerosol chemistry.

2.5. Regional Transport and Cross-Boundary Coupling

Particulate matter of size ($PM_{2.5}$) and ozone (O_3) pollution are not local but regional issues [30]. Trans-boundary movement of pollutants and precursors can occur via atmospheric circulation. $PM_{2.5}$ may be directly transported and O_3 may be transported directly and/or as its precursors which generate O_3 downwind. It is also possible for secondary aerosols to be created during transport, in which case pollution seen in one region could come partly from another region.

Regional transport is a governance challenge because the benefits of emissions reduction do not necessarily occur within the geographic boundaries of the jurisdiction that has the cost of control [31]. Pollution sources can cause significant air-quality impacts even though local sources are well controlled; and local sources can contribute significantly to the pollution in upwind areas. This spatial mismatch poses difficulties in matters of who is responsible, policy coordination and compensation. It also implies that if the effects of pollution inflows and spillovers are not taken into account in the local evaluation of efficiency, the latter may be biased.

Due to the regional nature of $PM_{2.5}$-O_3 pollution, coordinated governance between cities and provinces in airsheds is needed. Joint prevention and control should not be based on administrative boundaries alone, but should be based on atmospheric transport pathways, source-receptor relationships, and chemical sensitivity within the region [24]. It is necessary to find the focus of transmission corridors, dominant source areas and priority areas in the region for effective regional governance. When there is no coordination, local measures could result in spatial re-distribution of emissions or duplicate investments, leading to fragmented governance.

In addition to emissions and chemical transformations, meteorological conditions strongly regulate the accumulation and dispersion of $PM_{2.5}$ and O_3. Stagnant weather conditions, characterized by weak surface winds, reduced ventilation, and anticyclonic circulation, can suppress pollutant dispersion and promote the accumulation of primary pollutants and secondary products. At the local scale, the atmospheric mixing height determines the available volume for pollutant dilution; a shallow boundary layer, particularly during nighttime stable conditions, can substantially enhance near-surface pollutant concentrations. Pollutants and precursors accumulated within nocturnal residual layers may subsequently be transported or mixed downward when the boundary layer develops after sunrise, contributing to morning pollution episodes. Furthermore, pollutant recirculation processes can prolong regional pollution impacts. In coastal areas, sea-breeze circulation may transport urban emissions offshore during the day and return aged pollutants inland later, while valleys and complex terrains can promote repeated circulation and pollutant accumulation. Therefore, atmospheric governance strategies should consider meteorological variability through enhanced forecasting, dynamic emission-control measures during unfavorable dispersion conditions, and the integration of meteorological parameters into chemical transport models and governance efficiency assessments.

2.6. Theoretical Framework for Synergistic Control

The concept of synergistic control of $PM_{2.5}$ and O_3 can be explained by combining the principles of atmospheric chemistry, environmental economics, and regional governance theory. Synergistic control, from the point of view of the atmospheric chemistry, would involve identifying the synergistic response of $PM_{2.5}$ and O_3 to precursor reductions and designing emission strategies to maximise the co-benefits [32]. The environmental-economic view involves assessing the effectiveness of the use of resources in improving air quality, the economic costs, and the health and ecological impacts. It needs to be coordinated across policy goals, sectors, and jurisdictions in the context of regional governance.

There should be three fundamental parts to a complete synergistic control framework. The first is mechanism recognition, which helps clarify the interaction between $PM_{2.5}$ and O_3 via $PM_{2.5}$ precursor–$PM_{2.5}$ oxidant–$PM_{2.5}$ meteorology, and $PM_{2.5}$ –O_3 transport. The second is efficiency evaluation, which quantifies the governance inputs-outputs relationship in terms of multi-dimensional outputs such as pollutant reductions, health impacts, carbon mitigation and economic impacts. The third is path optimisation which seeks to identify alternative strategies for emission reduction which differ between regions and sectors, given a range of constraints [33].

This approach suggests that best governance does not necessarily mean the highest rate of emission reductions; but rather the most effective mix of actions within a certain range of chemical, economic and institutional parameters. For instance, a VOC-limited O_3 formation area will need to focus on controlling VOCs while an area where the nitrate contribution to $PM_{2.5}$ is high will need coordinated reduction of NO_x and NH_3 [21]. Process upgrading and clean energy substitution might be required in industrial areas while traffic emissions and the substitution of solvents and regional coordination might be emphasized in urban areas.

In general, the implementation of synergic $PM_{2.5}$ and O_3 control is a shift from pollutant-oriented to system-oriented management of the atmosphere [34]. Theoretically, it is an approach that acknowledges the complex adaptive nature of air pollution control, with chemical feedbacks, spatial spillovers, economic trade-offs, and institutional coordination at play. Governance measures for the future should be mechanism-oriented, regionally differentiated, adaptable and benefit-oriented. The main mechanisms linking $PM_{2.5}$ and O_3 formation and their implications for synergistic control are summarized in **Table 1**.

Table 1. Mian mechanisms linking $PM_{2.5}$ and O_3 formation in regional atmospheric environments.

Mechanism	Influence on $PM_{2.5}$	Influence on O_3	Implication for Synergistic Control
Shared precursors	NO_x, VOCs, SO_2, and NH_3 contribute to secondary aerosol formation	NO_x and VOCs drive photochemical O_3 production	Control strategies must target precursor combinations rather than single pollutants
Atmospheric oxidation capacity	Strong oxidation promotes sulfate, nitrate, and secondary organic aerosol formation	Strong oxidation accelerates photochemical O_3 generation	Oxidation capacity should be considered in both efficiency evaluation and pathway design

Table 1. *Cont.*

Mechanism	Influence on $PM_{2.5}$	Influence on O_3	Implication for Synergistic Control
VOCs–NO_x sensitivity	VOCs contribute to secondary organic aerosol; NO_x contributes to nitrate aerosol	O_3 response depends on VOC-limited or NO_x-limited regimes	Region-specific diagnosis is required before reducing NO_x or VOCs
Aerosol–radiation interaction	Aerosols affect photolysis and atmospheric stability	Reduced $PM_{2.5}$ may increase solar radiation and enhance O_3 formation	$PM_{2.5}$ reduction may alter O_3 chemistry and should be assessed dynamically
Heterogeneous reactions	Aerosol surfaces promote secondary inorganic aerosol formation	Heterogeneous reactions affect radical and reactive nitrogen cycles	Aerosol chemistry should be included in model-based policy assessment
Regional transport	$PM_{2.5}$ and precursors can be transported across regions	O_3 and its precursors can form or accumulate downwind	Joint regional control is necessary for airshed-level governance

3. Efficiency Evaluation of Regional Atmospheric Environment Governance

3.1. Connotation and Dimensions of Governance Efficiency

Evaluation of efficiency is one of the analytical tools to understand whether the regional governance of the atmospheric environment produces desirable environmental results with reasonable input of resources and the cost of the institutions [10]. Governance efficiency cannot only be understood as simply reducing pollutant levels when discussing synergistic $PM_{2.5}$ and O_3 control. Short-term air-quality gains may be achieved either through large-scale investment, which can lead to more inefficient governance, through temporary production restrictions, or through relocation of polluting industries, that can lead to more sustainable governance but may not necessarily be efficient. Thus, the efficiency of the governance of the atmosphere should be interpreted as a linkage between several inputs, several outputs, and other socioeconomic constraints.

Governance efficiency on the input side typically comprises of environmental investment, regulatory resources, pollution-control facilities, technological innovation, energy-structure adjustment, industrial upgrading, and administrative coordination [35]. On the output side, reductions in $PM_{2.5}$-O_3 and their precursors, better air-quality attainment rates, reduction in health risks, ecological benefits, reduction in carbon emissions, and economic co-benefits are included. The efficiency evaluation in the regional compound pollution control should take into account the undesirable outputs, including residual pollutant emissions, health losses, carbon emissions and cross-regional pollution transfer.

An important aspect of the synergistic governance of $PM_{2.5}$–O_3 is the fact that efficiencies could differ in the way pollutants are synergically controlled. It is possible for the $PM_{2.5}$ level to go down while O_3 goes up, which can make it appear better air quality but be an actual decrease in overall governance effectiveness. By the same token, if pollution is shifted from one region to another due to reduction in emissions elsewhere, the efficiency measurement for the region with the reduced emissions may be overstated. Therefore, an integrated approach that takes into account multi-pollutant interactions, regional spillovers and sustainability is required in assessing governance efficiency [11].

3.2. Indicator Systems for Evaluating Atmospheric Governance Performance

The indicator system for building construction is the basis of efficiency assessment. A scientifically sound indicator system should capture the complexity of the regional atmospheric governance system and be measurable and comparable. Traditional evaluation systems tend to be based on a single indicator, for example, $PM_{2.5}$ concentration, SO_2 emissions or air-quality compliance rates [36]. While these indicators are helpful, they cannot provide a complete picture of synergistic $PM_{2.5}$ and O_3 control as they lack consideration for secondary pollution formation, precursor interactions, and policy trade-offs.

Environmental, economic, technological, health and governance are all aspects of a comprehensive indicator system [13]. Environmental indicators can include annual average values of $PM_{2.5}$, maximum daily 8-hour average values of O_3, concentration of NO_2, SO_2, VOC, NH_3 emissions, their components as secondary aerosols and days of compound pollution. Pollution control investment, industrial output, energy consumption, environmental taxation and cost of emission reduction are some of the indicators of the economy. Technological indicators can include the share of clean-energy and end-of-pipe treatment efficiencies, upgrading of industrial processes, vehicle emission standards, and green innovation capacity. Health-related variables could be lower mortality rate, lower risk of respiratory and cardiovascular disease, increased population exposure, and reduced health costs. Examples of governance indicators include regulatory intensities, interregional coordination, capacity for policy implementation, and public participation.

But careful selection of indicators is important. Too many indicators can lead to redundancy and diminish the interpretability of the information, and too few indicators can result in the loss of essential mechanisms. Furthermore, the meaning of an indicator can vary from place to place. A reduction in NO_x emissions, for instance, can have a beneficial impact on $PM_{2.5}$ control because it can lead to a reduction in nitrate formation, but can have a negative impact in VOC-limited urban areas because it can increase O_3 formation [24]. So, assessment approach should not only monitor pollutants, but also chemical sensitivity and regional emission structure. The designer of a useful indicator system for synergistic governance should differentiate between direct outcomes, intermediate mechanisms and broader benefits.

3.3. Input–Output Efficiency Evaluation Methods

The input–output efficiency models are used extensively to assess the performance of environmental governance. Of these, one of the most popular non-parametric techniques is data envelopment analysis [37]. DEA benchmarks a set of decision making units (like cities, provinces or a city or province and its urban agglomerations) for relative efficiency, using input and output indicators. The benefit of this is that it can be used with several inputs and outputs and does not need to have a specific production function. This makes it applicable in complex environmental governance systems where both economic, environmental and social outputs exist.

The traditional DEA model, however, is not relevant in the governance of the atmosphere. It frequently makes assumptions about proportional changes in inputs and outputs and may fail to take into account unwanted outputs, like emissions of pollutants or losses of health. To address this, many slack-based measure models have been introduced. SBM models can incorporate excesses in the inputs and deficiencies in the outputs of an economic system, such as undesirable outputs, and consequently give a more realistic measure of the system's environmental efficiency [38]. Adverse outcomes in $PM_{2.5}$–O_3 governance can be undesirable $PM_{2.5}$ concentrations, O_3 exceedance days, NO_x emissions, VOC emissions, carbon emissions and population exposure risk.

Dynamic efficiency models like the Malmquist productivity index also can help identify the changes in governance efficiency over time [39]. This is crucial because atmospheric governance is a longer-term process which requires technological advancement, industrial transformation and policy learning. By decomposing efficiency change into technical efficiency change and technological progress, the Malmquist index can assist in determining whether efficiency improvements are due to better resource use or innovation or structural upgrading. Another type of model that can be useful for regional governance is spatial DEA and network DEA. Spatial models include spillovers of neighbouring regions, while network models split governance in several stages, including emission reduction, transformation of the atmosphere, improving concentration, and realizing health benefits.

Although input–output models are useful, they should be applied with caution. Efficiency scores are very dependent on the choice of indicators, data quality, modelling assumptions, and the definition of the decision-making units. A city might be efficient because it can have a lower base emission, a favourable meteorology, or pollution is transported away. Thus, efficiency models need to be used in conjunction with atmospheric modelling, source apportionment analysis and spatial econometric methods to increase the explanatory power [40]. **Table 2** compares commonly used methods for assessing efficiency and their applicability to $PM_{2.5}$–O_3 synergistic governance.

Table 2. Common methods for evaluating regional atmospheric governance efficiency.

Method	Main Function	Advantages	Limitations	Application in $PM_{2.5}$–O_3 Synergistic Governance
Data envelopment analysis	Measures relative efficiency among regions using multiple inputs and outputs	Suitable for complex multi-input and multi-output systems	Sensitive to indicator selection and does not directly explain chemical mechanisms	Can compare governance efficiency across cities or provinces
Slack-based measure model	Evaluates efficiency while considering input excesses and undesirable outputs	Handles pollutant emissions and environmental losses more realistically	Requires reliable undesirable-output indicators	Suitable for including $PM_{2.5}$ O_3, NO_x, VOCs, and carbon emissions as undesirable outputs
Malmquist productivity index	Measures dynamic efficiency change over time	Distinguishes technical efficiency change from technological progress	Less effective for explaining short-term chemical responses	Useful for tracking long-term governance improvement and policy learning
Spatial econometric model	Identifies spatial spillovers and regional dependence	Captures cross-boundary pollution and policy interaction	Requires spatial weight matrices and careful interpretation	Useful for evaluating regional transport and neighboring-region effects
Chemical transport model	Simulates pollutant formation, transport, and transformation	Mechanism-based and suitable for scenario analysis	Data-intensive and uncertain under complex emission conditions	Essential for testing $PM_{2.5}$ –O_3 response to precursor reductions
Integrated assessment model	Links air quality, economy, health, and policy costs	Supports multi-objective decision-making	May simplify atmospheric chemistry or regional heterogeneity	Useful for selecting cost-effective and health-oriented control pathways

3.4. Integration of Environmental, Economic, Health, and Social Benefits

One of the most important issues for assessing the efficiency of regional atmospheric governance is how to incorporate multiple benefits. Air pollution control leads to direct environmental benefits but also to impacts on health, economy, climate, and social issues [41]. Although both $PM_{2.5}$ and O_3 have important health impacts, their exposure patterns, seasonal characteristics, and populations affected vary. The effects of $PM_{2.5}$ are often linked to chronic exposure, whereas those of O_3 pollution are more likely to manifest during the warm season, potentially resulting in short-term respiratory effects. As such, an effective governance approach to reducing $PM_{2.5}$ and increasing O_3 levels could have mixed or partial health impacts.

Pollution-control costs are not the only benefits to consider in an economic evaluation. Improved air quality can benefit medical spending, labor productivity, urban attractiveness, and green industrial development. Meanwhile, industries, transport systems, and energy-intensive sectors with high emissions might face adjustment costs due to emission reduction. Therefore, the benefits and costs of efficiency, and their distribution among sectors and populations, should be taken into account [42].

The incorporation of carbon reduction grows in significance. There are a number of air pollution control measures, including coal substitution, renewable energy, electrification of transport, and industrial energy-efficiency improvements, that can help lower air pollutants and greenhouse gases. Not every end-of-pipe control yield carbon benefits; however, some may increase energy use. A high-efficiency governance pathway should, therefore, maximize the co-benefits between the reduction of $PM_{2.5,}$ the mitigation of O_3, the reduction of carbon, and the protection of health [10].

Social benefits encompass environmental justice, community satisfaction, risk communication, and institutional trust [43]. Even if regions do not have the top exposure-reduction efficiency scores, they may need to use more rigorous exposure-reduction measures for vulnerable populations. Here, efficiency assessment should not be considered without regard to fairness. A governance process that leads to average regional improvement but leaves disadvantaged communities vulnerable to high pollution is not socially welfare efficient.

3.5. Spatial–Temporal Heterogeneity of Governance Efficiency

The efficiency of atmospheric governance is highly heterogeneous across spatial and temporal scales [44]. Industries, energy systems, emission intensities, transport situation, meteorological conditions, and governance capacities vary across regions. High pressure of precursor emissions and $PM_{2.5}$ pollution can be expected in heavy industrial areas, and high pressure of O_3 pollution in large urban areas, as a consequence of traffic emissions, solvent use, and VOCs–NO_x sensitivity. Agricultural regions can be a major source of NH_3, which can impact secondary inorganic aerosol (SIA) formation. Thus, the efficiency results from the same policy measure can vary from one region to another.

The spatial heterogeneity is further increased by regional transport [6]. Upwind areas can affect pollution, and central cities downwind can be impacted by surrounding industrial belts or transportation corridors. Local responsibility and contribution, as calculated based on local emissions and air quality, may not reflect the actual responsibility and contribution. Strictly speaking, a low efficiency region can also be an efficient region if the external pollution influx is large, and vice versa. Spatial source-receptor relationships should therefore be considered in the efficiency assessment.

Governance efficiency is dynamic over time, depending on the cycling of policy changes, technological advances, economic restructuring, meteorological variation, and seasonal chemical regimes [11]. The concentration of $PM_{2.5}$ pollution is usually higher in winter when the meteorological conditions tend to be less favorable, while the concentration of O_3 pollution is generally higher in spring and summer when the weather is more favorable for the formation of O_3. So, annual-average indicators can mask seasonal compromises. The air quality for $PM_{2.5}$ control may be good in winter, whereas it may be poor for O_3 mitigation in summer. Hence, assessments of efficiency should not rely exclusively on annual averages but should also consider analyses for each season and each episode.

Long-term temporal evaluation is also required because the marginal benefit of control measures may decline over time. In the initial stages of pollution control, sizeable pollution reductions can be accomplished by phasing out polluting capacity and end-of-pipe pollution abatement. The further reduction of emissions is more difficult, necessitating more sophisticated measures, including species control of VOC, control of NH_3, regional coordination, and low-carbon structural transformation [45]. This change implies that the assessment of efficiency must be flexible and adapt to the evolving pollution mechanisms and governance priorities.

3.6. Limitations of Existing Efficiency Evaluation Approaches

While various approaches have been developed to assess the efficiency of atmospheric governance, gaps remain in the existing literature. First, current evaluations largely rely on $PM_{2.5}$ or traditional pollution levels and fail to adequately account for O_3 or the non-linear relationship between $PM_{2.5}$ reduction and O_3 [24]. This could cause an overestimation of governance performance in areas where PM2.5 has decreased and O_3 has increased. If a synergistic assessment framework is used, PM2.5 and O3 should not be treated as independent pollutants.

Secondly, there are existing models that do not explicitly include atmospheric chemical mechanisms [9]. DEA, SBM, and efficiency models in general can measure relative performance, but cannot explain what the response of air quality is for a chosen emission reduction strategy. Efficiency scores can be descriptive rather than diagnostic unless they are integrated into chemical transport models or derived from sensitivity analyses of photochemical conditions. This restriction is particularly relevant to O_3 control, where a reduction in NOx under different VOC-NO_x regimes can yield different outcomes.

Third, spillover effects are not sufficiently taken up regionally. Generally, administrative regions are used as evaluation units; however, the atmospheric processes do not occur along administrative boundaries. Without accounting for cross-boundary transport, assessments of responsibility and of policy effectiveness and efficiency may be skewed. Future research is needed to include source-receptor modeling, spatial econometrics, and regional input–output analysis in order to gain a more comprehensive understanding of both atmospheric and economic linkages [46].

Fourth, there is a lack of integration of health, carbon, and equity benefits. Pollutant concentration or emissions is used as an output in many efficiency evaluations, but exposure of the population, avoided mortality, climate co-benefits or distributional impacts are not fully quantified [47]. This makes the results of evaluations less policy-relevant. A region with a low population but high emissions reduction can earn a high score, and a region with high vulnerability and low emissions reduction can earn a low score. Therefore, we need to strengthen the exposure-weighted and welfare-oriented indicators.

Lastly, there is uncertainty about the data. Uncertainties exist in the emission inventories, VOC species profiles, NH_3 emissions, regional transport contribution, and health exposure functions [24]. The uncertainty can have implications for efficiency scores and policy recommendations. Uncertainty analysis, scenario comparison, and robustness testing should be included in future evaluations. More importantly, efficiency evaluation should not remain a one-dimensional ranking tool but should develop to become a decision-support framework to uncover mechanisms, identify inefficiencies, and suggest optimized regional emission reduction pathways.

In conclusion, it is proposed to shift the perspective of efficiency evaluation of regional atmospheric environment governance from one-pollutant outcome assessment to multi-pollutant, mechanism-informed, and welfare-oriented assessment [11]. The most meaningful indicator of synergistic control of $PM_{2.5}$ and O_3 is not just a reduction in concentrations; if pollution is reduced in a way that is coordinated through regional governance, it improves health, reduces carbon emissions, and achieves equitable development. The most meaningful indicator of synergistic control of $PM_{2.5}$ and O_3 is not simply a decline in concentration, but coordinated pollution reduction through regional governance, improved health, carbon mitigation, and equitable development by scientifically optimized and economically efficient pathways.

4. Emission Reduction Pathways for Coordinated $PM_{2.5}$ and O_3 Mitigation

4.1. Sectoral Emission Characteristics: Industry, Power, Transport, Residential, and Agriculture

To successfully coordinate $PM_{2.5}$ and O_3 mitigation efforts, an understanding of precursor emissions at the sector level, as well as precursor response in the atmosphere, is needed. A complex mixture of primary particles, NO_x, VOCs, SO_2, NH_3, and carbonaceous aerosols forms regional air pollution [21]. These pollutants come from various sectors, and their proportions differ across regions, seasons, and levels of economic development. Thus, a consistent pathway for emission reduction is not possible. Rather, they should be developed based on the prevailing sources, chemical sensitivity, and regional transport patterns.

Industrial sources can be significant contributors to SO_2, NO_x, VOCs, and primary particulate matter (PM). Industrial and steel manufacturing, cement making, petrochemicals, nonferrous metals, and chemical manufacturing all emit direct emissions and secondary aerosol precursors. In many industrial areas, end-of-pipe control has already reduced significant amounts of SO2 and dust; however, VOCs, such as those from incomplete combustion, solvent use and storage tanks, and leaks, are difficult to control. This sector has a specific importance in the context of coordinated action for $PM_{2.5}$ and O_3 control because of the complexity of VOC species [29].

Historically, the power sector has been a major source of SO_2, NO_x, and primary particulate emissions. Many areas have seen a significant reduction in emissions from coal-fired power plants through ultra-low-emission retrofits, dust removal, desulfurization, and denitrification. Power-sector control remains significant in areas with high coal dependence and in areas where electricity demand rises with electrification. The great difficulty is to prevent the transition to more electric transportation, industrial, and building fleets from merely shifting emissions from end-use sectors to the power sector [48].

Transport emissions are strongly linked to urban O_3 formation, as vehicles emit NO_x and VOCs in the urban area with high photochemical activity [49]. NO_x and primary particles can be emitted at high levels from diesel vehicles, heavy-duty trucks, non-road machinery, and shipping, and gasoline vehicles and fuel evaporation can be significant VOC sources. Transport control is very beneficial to health because pollutants are emitted close to where people are exposed. NO_x reduction from traffic should be coordinated with VOC reduction; however, particularly in VOC-limited cities, reductions in NO_x alone may exacerbate O_3.

These include consumer products with solvents, cooking, small boilers, heating, and the combustion of coal and biomass at residential and commercial facilities. The individual sources may be small, but they can add up to a significant amount during periods of winter heating. Applications of fertilizer, livestock production, and agricultural waste management are particularly relevant for NH_3 emissions. While NH_3 control has been underappreciated in many instances, it is critical for lowering emissions of ammonium nitrate and ammonium sulfate, particularly when SO_2 and NO_x emissions have been reduced [27]. So, reducing agricultural emissions should be part of the regional process of atmospheric governance instead of a rural environmental problem.

4.2. VOCs–NO_x Sensitivity and Differentiated Precursor-Control Strategies

The nonlinear relationship between VOCs and NO_x is crucial to the effectiveness of O_3 mitigation. However, in VOC-limited regimes (typical in dense urban and industrial settings), VOC availability determines the amount of O_3 formed. Under these conditions, a decrease in NO_x can lead to a decrease in the nitric oxide titration and an increase in O_3. Hence, VOC control should be targeted, especially by reducing highly reactive VOC species. NO_x reduction is usually more effective at reducing O_3 formation in NO_x-limited regimes that typically occur in downwind and rural and suburban areas [29].

This different sensitivity is key for synergistic $PM_{2.5}$ and O_3 mitigation. Reducing NO_x can reduce nitrate aerosol and nitrogen deposition, but may affect O_3. However, if the design of NO_x control is suboptimal, it can lead to declines in $PM_{2.5}$ and deterioration in O_3, thereby lowering overall governance efficiency. On the other hand, VOC reduction with good targeting can reduce the formation of O_3 and secondary organic aerosol, resulting in synergies. Hence, the use of diagnostic tools like observation-based models, emission-ratio analysis, satellite retrievals, radical chemistry indicators, and chemical transport modeling should form the basis for precursor-control strategies [32].

Total VOC emissions should not be the only measure for controlling VOCs. The ozone formation potentials and SOA yields of VOCs vary from one VOC to another. Solvent-derived aromatics, industrial and vehicular alkenes, and oxygenated VOCs (OVs) produced in industrial processes and consumer products can be very reactive. A sophisticated VOC control strategy should be able to identify priority species and VOC sources, rather than making broad, low-efficacy reductions. Specific actions like leak detection and repair, using low-VOC raw materials, vapor recovery, closed production systems, and better management of solvents can offer specific benefits [50].

Differentiated strategies also need to be used for each season. During the summer, high sensitivity to VOCs and NO_x is important due to strong radiation and high temperatures. Nitrate aerosol formation could be more significant during winter months, and controlling NO_x and NH_3 could be more beneficial for $PM_{2.5}$. Thus, seasonal emission control would be beneficial for enhancing efficiency through policy measures that coincide with the atmospheric chemical conditions [23].

4.3. Structural Adjustment, Energy Transition, and Clean Technology Substitution

It is not possible to achieve long-term synergistic control without end-of-pipe treatment. Structural adjustment and energy transition are necessary as they cut emissions at the source and may offer co-benefits on air pollution, carbon mitigation, and industrial upgrading [51]. Industrial restructuring can help lower emissions by removing obsolete production capacity, improving resource use, encouraging the circular economy, and shifting from less to more carbon-efficient industries. It should be emphasized, however, that in the process of structural adjustment, the transfer of polluting activities from one geographic location to another should be avoided, as this may lead to an improvement in air quality in the area where the pollution source is removed, but to an increase in pollution transfer to the other area.

Energy transition is a fundamental approach to reducing SO_2, NO_x, primary particles, and carbon emissions [52]. Using renewables instead of coal and natural gas, if appropriate, and low-carbon electricity can help cut emissions from combustion. In urban areas, clean heating, building energy efficiency, and electrification will help lower the number of winter $PM_{2.5}$ events associated with diffuse coal and biomass combustion. Overall, buses, taxis, private vehicles and logistics vehicles can be electrified, minimizing near-road exposure to NO_x and particles in the transport sector. However, the environmental impacts of electrification will depend on the ‘cleanliness’ of the electricity source and the lifecycle of batteries.

Clean tech substitution is also crucial in the industrial sector [53]. The direct emission and precursor formation can be minimized with low-NO_x combustion, high-efficiency boiler, electric furnace, hydrogen-based metallurgy, green ammonia, clean raw materials and low-solvent manufacturing. The use of water-based, powder or radiation-curable materials as substitute for VOC-intensive materials can lower the formation of O_3 and secondary organic aerosols in VOC intensive industries. Precision fertilization, slow-release fertilizers, better manure management and livestock feeding optimization for agriculture can lower NH_3 emissions.

One of the problems is that, often, structural and technological pathways involve a higher initial investment and longer implementation time than end-of-pipe measures. The advantages they offer, however, are more long-lasting and penetrating. Thus, these measures should not be discounted due to their less immediate reduction in emissions in the short term in the governance efficiency evaluation. Avoided future costs, technological learning, health benefits and climate co-benefits need to be taken into account for long-term pathway optimization [8].

4.4. End-of-Pipe Control and Process Optimization

End-of-pipe control remains an indispensable component of atmospheric governance, particularly for sectors with large point-source emissions [54]. Technologies such as flue gas desulfurization, selective catalytic reduction, electrostatic precipitators, fabric filters, wet scrubbers, and VOC treatment systems have played an important role in reducing conventional pollutants. These measures are especially effective when emission sources are concentrated, monitoring is feasible, and compliance can be enforced.

However, the marginal benefits of end-of-pipe control may decline after major sources have been retrofitted. Further reductions may require higher costs, more precise management, and better operation and maintenance. In some cases, pollution-control devices may reduce one pollutant while increasing energy consumption or generating secondary waste. For example, inefficient VOC treatment may produce incomplete oxidation by-products, while some control technologies may increase carbon emissions due to additional energy demand [50]. Therefore, end-of-pipe control should be evaluated not only by removal efficiency but also by lifecycle environmental performance.

Process optimization can complement end-of-pipe control by reducing pollutant generation during production [55]. Cleaner raw materials, closed-loop systems, improved combustion control, heat recovery, fugitive-emission management, and digital monitoring can reduce emissions before they enter treatment systems. For VOC control, process optimization is particularly important because fugitive emissions from storage, transfer, mixing, coating, and leakage are often difficult to capture through terminal treatment alone. In petrochemical and chemical industries, leak detection and repair programs, vapor balancing, and sealed sampling can significantly reduce reactive VOC emissions.

The integration of end-of-pipe treatment with process optimization represents a shift from passive control to active pollution prevention. This shift is important for coordinated $PM_{2.5}$ and O_3 mitigation because secondary pollution is sensitive to emission composition and timing. Stable, continuous, and well-managed emission reductions are often more effective than temporary or emergency controls [55].

4.5. Nature-Based and Urban Planning Interventions

While reducing direct emissions is necessary for improving air quality, NbS and urban planning interventions can complement these efforts. Urban green spaces, ecological corridors, vegetation barriers, and regional land-use planning have various effects that influence pollutant dispersion, intensity of heat-islands, exposure, and micro climatic conditions [56]. These interventions can also indirectly control O_3 formation and exposure to the population by reducing urban temperature and enhancing the spatial ventilation.

The contribution of vegetation to $PM_{2.5}$ and O_3 control needs to be evaluated, however. Biogenic VOCs production by some plant species can be a source of O_3 and SOA formation at high NO_x conditions. For urban greening, therefore, it is necessary to favor low-emission species and take into account local photochemical sensitivity. The inappropriate design of green belts can also affect the air exchange in street canyons and affect the concentration of near-road pollutants [24]. Therefore, NbI interventions need to be complemented by weather forecasting and urban design and cannot be considered universally beneficial.

The potential of urban planning for reducing emissions lies in the potential of reorienting mobility, land use, and energy demand [57]. Compact development, transit-oriented design, mixed land use, pedestrian infrastructure, and low-emission zones can help to reduce vehicle reliance and transport emissions. Shifting from areas with high emissions from industrial activities to areas with inhabitants can lessen exposure, but the greater the distance, the higher the emissions of commuters or the greater the risk can be passed on from the industrial activity to peripheral areas. Thus, any intervention based on planning needs to focus on reducing emissions, reducing exposure, economic accessibility, and environmental justice.

At the regional level, the use of ecological zoning and optimization of industrial layout can decrease the accumulation of pollution in sensitive areas and avoid the concentration of high-emission industries in poorly ventilated regions and transport corridors. These are especially relevant in cities or urban areas where the use of land, land use, industrial development, and the transport of air through the atmosphere are tightly linked [57].

4.6. Scenario Simulation and Cost–Benefit Assessment of Alternative Emission Reduction Pathways

Scenario simulation is essential for comparing alternative emission reduction pathways under complex $PM_{2.5}$–O_3 interactions [58]. Because atmospheric responses are nonlinear, policy effectiveness cannot be reliably inferred from emission reduction quantities alone. Chemical transport models, observation-based models, source-apportionment tools, and integrated assessment models can be used to simulate how different sectoral and regional control measures affect pollutant concentrations, exposure, health outcomes, and economic costs.

Scenario design should include both single-sector and multi-sector pathways. For example, one scenario may emphasize industrial VOC reduction, another may focus on transport NO_x control, and a combined scenario may integrate VOC, NO_x, NH_3, and primary PM control. Comparing these scenarios can reveal synergistic effects, trade-offs, and marginal benefits [58].

In regions where $PM_{2.5}$ has declined but O_3 remains high, scenarios should pay particular attention to VOCs–NO_x sensitivity and the possibility that further $PM_{2.5}$ reduction may alter photolysis and atmospheric oxidation [58]. Cost–benefit assessment can be used to help choose efficient pathways. The costs consist of pollution-control equipment, operating and maintenance costs, industrial restructure, energy substitution, monitoring, enforcement, and social adjustment [59]. The benefits include reduced premature mortality, reduced disease burden, improved labor productivity, ecosystem protection, improved visibility, reduced carbon emissions, and better quality of life. Exposure-based evaluation is more important because the health benefits are likely to outweigh the majority of the risks. Social benefits from an emission cut in a high-population-density area could be larger than those in a low-density area.

Multi-objective optimization can also assist in developing a policy by considering multiple environmental objectives, economic costs, technological feasibility, carbon constraints, and equity considerations [60]. Optimization should not converge to a single universal pathway, but rather provide a collection of potential pathways for various regions. The emphasis for a high-efficiency pathway for a heavy industrial region could be on industrial restructuring, clean energy substitution, and NH_3 coordination, while for a megacity, it could be on reactive VOC control, traffic electrification, solvent management, and regional transport coordination.

What's most effective about scenario simulation and cost–benefit assessment is their power to shift the decision-making process from an experience-based approach to an evidence-based approach to selecting pathways. But uncertainty needs to be addressed explicitly. These uncertainties exist in emission inventories, meteorological projections, profiles of VOC species, health-response functions, and costs of technology [24]. They should then compare several options, test their sensitivity assumptions, and indicate what can still be done to benefit in different future scenarios.

From a comprehensive mitigation perspective, coordinated $PM_{2.5}$ and O_3 mitigation needs an integrated emission reduction pathway which incorporates source-specific control, chemical-sensitivity diagnosis, transformation of the structure, clean technology substitution, process optimization, urban planning, and regional scenario assessment [61]. Reducing emissions is not just a matter of reducing emissions of the right pollutant in the right place at the right time; it is a matter of reducing the right emissions from the right source in the right region at the right time. Such a pathway can ensure lasting improvements in regional atmospheric environmental quality only if it is based on efficient mechanisms. The key emission features, emission control options, co-benefits, and trade-offs are listed below in **Table 3**.

Table 3. Sector-specific emission reduction pathways for coordinated $PM_{2.5}$ and O_3 mitigation.

Sector	Major Emissions	Control Measures	Expected Synergistic Benefits	Potential Trade-Offs Or Concerns
Industry	SO_2, NO_x, VOCs, primary PM, secondary aerosol precursors	Clean production, low-VOC raw materials, leak detection and repair, desulfurization, denitrification, dust removal	Reduces secondary $PM_{2.5}$, O_3 precursors, and industrial exposure risks	High investment costs; risk of relocating pollution-intensive industries
Power generation	SO_2, NO_x, primary PM, CO_2	Renewable energy substitution, ultra-low-emission retrofits, and energy-efficiency improvement	Reduces combustion-related $PM_{2.5}$ precursors and carbon emissions	Electrification benefits depend on the power sector's cleanliness
Transport	NO_x, VOCs, primary PM, black carbon	Vehicle electrification, public transport, low-emission zones, fuel-quality improvement, control of heavy-duty diesel vehicles	Reduces near-road exposure, NO_x, VOCs, and primary particles	NO_x reduction alone may increase O_3 in VOC-limited areas
Residential and commercial	Primary PM, VOCs, NO_x, combustion emissions	Clean heating, building energy efficiency, replacement of scattered coal and biomass, low-VOC products	Reduces winter $PM_{2.5}$ episodes and local exposure	Scattered sources are difficult to monitor and regulate
Agriculture	NH_3, dust, biomass-burning emissions	Precision fertilization, manure management, slow-release fertilizers, straw-burning control	Reduces ammonium nitrate and ammonium sulfate formation	Agricultural NH_3 control may face economic and behavioral barriers
Urban planning and land use	Traffic-related emissions, exposure concentration, heat-island effects	Transit-oriented development, ventilation corridors, low-emission urban zones, low-biogenic-VOC greening	Reduces population exposure and supports long-term emission reduction	Poor vegetation choice may increase biogenic VOC emissions

5. Regional Path Optimization and Governance Synergy

5.1. Regional Coordination Mechanisms and Joint Prevention-Control Systems

Path optimization is important at the regional level due to the fact that $PM_{2.5}$ and O_3 pollution do not respect administrative boundaries [33]. The pollutants and their precursors can be transported between cities and provinces and secondary pollutants can develop during transport. Therefore, the air quality in one area can be influenced by emissions from other areas as well as by local emissions sources. This spatial interdependence can lead to partial benefits from isolated local governance, duplication of costs or even pollution displacement. Hence, the coordination of the different regions is not an auxiliary policy action, but an essential action for the implementation of effective synergistic control of $PM_{2.5}$ and O_3.

Joint prevention-control systems are institutional foundations for regional atmospheric governance [24]. Typically, these systems comprise of a single monitoring system, shared emission inventories, co-ordinated response plans, joint air-quality forecasting, and synchronised pollution control measures during pollution episodes. Their success will rely on the ability of regions to shift from campaign-style cooperation to stable, rule-based and science-driven coordination. In many instances, regional cooperation will be at its strongest when there is a severe pollution event happening, and weaker in the day to day of governance. This will reduce the predictability and continuity of emission reductions.

The regional coordination mechanism should be more effective based on airshed management, not administrative division. Airsheds are indicative of the pathways in the atmosphere, regional circulation patterns, and source-receptor relations. If the governance units are aligned with pollution transmission properties, a more coherent policy coordination is possible. This is especially relevant for $PM_{2.5}$ and O_3 control, as the processes by which they are formed and transported are different. While $PM_{2.5}$ control might be more concerned with the direct transport of particles and influence on secondary aerosol precursors, O_3 control needs to take into account downwind production of O_3 from transported VOCs and NO_x. So, the regional coordination should be pollutant-specific, seasonal and pathway-specific [45].

But there are institutional obstacles to coordination as well. In areas where the local economy relies heavily on energy consumers, local governments might focus on economic activity, jobs and revenue, among other concerns. Unequal control burdens arise from the different structures of industries and the capacity of the environment. Regional cooperation can be superficial if there are no clear benefit-sharing and responsibility allocation processes. So optimization of governance pathways needs not only to be done technically in terms of modeling but also institutionally in the sense of innovating institutions [62].

5.2. Optimization Models for Emission Reduction Allocation and Policy Design

The problem of emission reduction allocation is one of the main problems in regional path optimization [12]. The challenge is how to divide the responsibilities for reducing emissions between regions, sectors and pollution sources in order to maximise environmental and social benefits with minimum cost. Conventional allocation techniques are based on targets set by administration, past emissions or standard reduction rates. While they are easy to apply, they could fail to take into account regional variations in the intensity of emissions, sensitivity of the atmosphere, economic capacity and marginal abatement costs.

Optimization models offer a more structured approach to designing policies. To find emission reduction ways according to several constraints, one can use linear programming, nonlinear programming, multi-objective optimization methods, genetic algorithms and robust optimization. The constraints can range from air quality standards, carbon emission caps, industrial production, availability of technologies, policy costs, health-risk limits, to equity needs [63]. For $PM_{2.5}$ –O_3 synergistic control, the optimization models should account not only for the amount of emission abatement but also on the chemical effectiveness of the emission abatement of various precursors.

One of the greatest challenges is the non-linear relationship of the emission reductions of VOC and NO_x with the O_3 reductions [24]. Optimal reduction plan for $PM_{2.5}$ may not be optimal for O_3. For instance, a significant decrease in NO_x can be beneficial for decreasing nitrate aerosol, but can also lead to an increase in O_3 in VOC-limited urban areas. On the other hand, reduction of reactive VOC can also result in the reduction of O_3 and SOM, although the extent of the reduction will vary depending on the species involved and the chemical conditions. So, chemical sensitivity parameters should be incorporated into the optimization model or coupled with an atmospheric model to avoid misleading conclusion.

The potential for marginal abatement costs should also be taken into account in the design of the policy. There are some sectors where significant emissions reductions can be achieved at relatively low cost, and others where emissions reductions will be expensive to achieve through technological transformation. But it is not enough to minimize costs. Reducing emissions in concentrated areas could lead to more health benefits than the same amount of emission reduction in less dense areas. The same is true for O_3 benefits: controlling highly reactive VOCs yields greater benefits than controlling less reactive ones. Therefore, the best allocation should consider integrated marginal benefits, such as concentration reduction, exposure reduction, carbon co-benefits, and ecosystem protection [58].

5.3. Coupling of Air-Quality Models, Economic Models, and Decision-Support Systems

Science simulation and policy evaluation must be combined to optimize paths in the region. Air-quality models can project impacts of emissions reductions on $PM_{2.5}$, $O_{3,}$ and precursor levels, and economic models can calculate control costs, industrial impacts, energy transitions, and welfare impacts [61]. These outputs can be linked to decision-support systems and analyzed to provide policy-relevant pathways based on model results.

Chemical transport models are especially significant since they depict processes in the atmosphere, including emissions, transport, chemical transformation, deposition, and interaction with meteorology [64]. They can predict the impact of emission abatements in one region on air quality in another region and identify source-receptor relationships. Air-quality models are required for O_3 control because sensitivity to precursors can't be fully captured by fixed emission ratios. They facilitate the separation of the contributions of primary particles, sulfate, nitrate, ammonium, and secondary organic aerosol to $PM_{2.5}$ control.

Economic models evaluate feasibility and economic costs in complement to atmospheric simulations [11]. Input-output models may be used to estimate the impacts of emissions reductions in one sector on other sectors of the economy. Computable general equilibrium models can assess the wider economic adaptation responses to policy scenarios. Cost-benefit analyses can be used to compare costs to health and environmental benefits. These tools can be used together to find pathways that are not only environmentally effective but also economically realistic.

However, there are several limitations to model coupling. The high-resolution emission inventories, meteorological data, and chemical mechanisms needed for atmospheric models are all uncertain. The economic models might oversimplify technological change, behavioral responses, and regional inequality. Technically complex decision-support systems can be elaborate yet still rely on assumptions built into the model design. Hence, model results should not be regarded as accurate forecasts. They are considered organized evidence to measure the options for policies in an uncertain world [64].

An advanced decision support system should enable feedback between monitoring data, simulation, policy implementation and performance evaluation. It is not a one-size-fits-all optimal solution; rather, it should enable adaptive governance. Optimal pathways need to be revised as emissions, technology, climate, and socioeconomic conditions evolve. This is particularly crucial for $PM_{2.5}$ and O_3, since the atmospheric chemistry and precursor sensitivity could vary with time as emission structure changes [32].

5.4. Cross-Regional Responsibility Sharing and Compensation Mechanisms

We need to share responsibility across regions, as the costs and benefits of atmospheric governance are often regionalized. The potential emission reduction costs are high in upwind areas, and the air-quality benefits are large in downwind areas. Industrial areas can deliver goods and energy to more distant areas in the region, and also have a higher environmental burden. Regional cooperation can face resistance and implementation challenges if there are no feasible mechanisms for fair responsibility sharing [7].

The allocation of responsibility should be determined according to the production responsibility, consumption responsibility, contribution to the atmosphere, economic capacity and distribution of benefits. Production-based responsibility focuses on emissions arising in a region. Consumption-based responsibility accounts for emissions generated by the production of goods and services consumed outside the country. Atmospheric contribution is a concept based on source-receptor relationships and the actual effects of regional emissions on the air quality at downwind receptors. Economic capacity accounts for the fact that wealthier areas may have the capacity to invest in cleaner technologies. Benefit Distribution takes into account who benefits most from the reduction in pollution [65].

There are ways to make regional cooperation more fair and stable through compensation [7]. Incentive alignment can be achieved through ecological compensation, fiscal transfer payments, joint pollution control funds, technology sharing programs, and regional emissions trading. For instance, downwind areas that may see emission reductions due to upwind areas could provide financial or technical assistance to upwind emission control projects. Likewise, economically developed urban areas can enable cleaner industrial transitions in neighboring manufacturing areas that contribute to regional pollution.

But the compensation schemes have to be well thought out. A single objective of emission reduction quantities might be sufficient to drive low-quality or short-term emission reductions. When not considering the effectiveness of the atmosphere, money can be spent on measures that provide less-than-optimal air-quality benefits. It can lack transparency and undermine public trust if it fails to do so. Hence, compensation should be tied to confirmed reductions in emissions and to modeling the source's benefits to the receptor, reductions in health risks, and long-term structural improvements [66].

Environmental equity should also be one aspect of cross-regional responsibility sharing. High-polluting industries should not be transferred to less developed areas of the country as part of pollution-control policies. This could lead to reductions in air quality in the center of urban areas, but to increases in exposure and health risks in the fringe areas. Spatial transfers of environmental burden must be avoided and a fair governance system must ensure even distribution of both burden and benefit [47].

5.5. Policy Synergy among Air Pollution Control, Carbon Reduction, and Public Health Protection

Synergistic governance should extend beyond the coordinated control of $PM_{2.5}$ and O_3 to include carbon reduction and public health protection [33]. Air pollution control and climate mitigation are closely interconnected, as many sources of $PM_{2.5}$ precursors and GHGs are linked to fossil fuel use, industrial processes, transport, and residential energy generation. Renewable energy replacement, energy-efficiency improvements, electrification, industrial retrofits, and clean heating can help reduce air pollutants and carbon emissions.

But some air pollution control options have carbon co-benefits [41]. Energy is needed in some end-of-pipe technologies, which can lead to higher indirect CO_2 emissions. Likewise, some low-carbon measures may have complex impacts on air quality, depending on how they are managed. For instance, while electrification will lower tailpipe emissions, its overall impact will depend on the power generation mix. When biomass combustion is inefficient, it can contribute to particulate and VOC emissions while reducing fossil carbon emissions. Hence, policy synergy is not about merely putting policies together, but about thinking in terms of their entire life cycle.

Another criterion to consider for path optimization is public health protection [10]. Both $PM_{2.5}$ and O_3 are harmful to human health, but in different ways. Both $PM_{2.5}$ and O_3 negatively affect human health, but they do so through different spatial and temporal exposures. Concentrations of $PM_{2.5}$ tend to be associated with longer-term chronic health effects, while O_3 is strongly correlated with photochemical episodes during warm seasons and with respiratory health effects. A policy that lowers $PM_{2.5}$ concentrations and raises O_3 concentrations during the summer could not be the most health-beneficial option. Hence, in optimizing for health, population exposure, vulnerable groups, seasonal risk, and pollutant-specific health-response relationships should be taken into account.

The integration of health benefits can change policy priorities. The health benefits of emission reductions in densely populated cities may be greater than those in more remote industrial areas, even if emissions are lower. Emissions from traffic, residential combustion, and solvent use can yield substantial benefits for reducing exposure, as these sources are near population centers. Designing health-oriented policies can thus enhance the social efficiency of atmospheric governance [17].

Additionally, there is a need to coordinate the authorities responsible for the environment, energy, industry, transport, agriculture, and public health in order to have policy synergy [13]. The lack of coordination in governance can result in inconsistent targets and duplicated investments. However, energy policy might aim to increase electrification, environmental policy might aim to reduce NO_x emissions, and health policy might aim to reduce exposure, all of which must be woven together into a coherent pathway. Co-benefits can be reinforced and trade-offs avoided through multi-objective governance. The key dimensions of regional path optimization and governance synergy are organized in **Table 4**.

Table 4. Framework for regional path optimization and governance synergy.

Optimization Dimension	Core Objective	Main Tools or Mechanisms	Relevance to $PM_{2.5}$–O_3 Control
Regional coordination	Align control measures across airsheds	Joint prevention-control systems, unified monitoring, shared forecasting, and regional emergency response	Addresses cross-boundary transport and secondary formation
Emission allocation	Distribute reduction responsibilities efficiently	Multi-objective optimization, marginal abatement cost analysis, source-receptor modeling	Identifies where and which emissions should be reduced first
Chemical sensitivity diagnosis	Avoid adverse pollutant responses	VOCs–NO_x sensitivity analysis, observation-based models, chemical transport models	Prevents NO_x control from worsening O_3 under VOC-limited conditions
Economic efficiency	Maximize benefits under cost constraints	DEA, SBM, cost–benefit analysis, integrated assessment models	Links environmental improvement with governance inputs and economic feasibility
Health-oriented governance	Reduce population exposure and disease burden	Exposure assessment, health-risk valuation, vulnerable-population analysis	Prioritizes measures with the greatest public health benefits

Table 4. *Cont.*

Optimization Dimension	Core Objective	Main Tools or Mechanisms	Relevance to $PM_{2.5}$–O_3 Control
Carbon and air-quality synergy	Coordinate pollution control with climate targets	Clean energy transition, electrification, lifecycle assessment, industrial upgrading	Enhances co-benefits between $PM_{2.5}$ reduction, O_3 mitigation, and carbon neutrality
Equity and compensation	Balance regional costs and benefits	Ecological compensation, fiscal transfers, regional funds, and technology sharing	Prevents pollution transfer and supports fair responsibility sharing
Adaptive governance	Update pathways based on changing conditions	Real-time monitoring, satellite data, AI forecasting, dynamic policy adjustment	Enables timely responses to changing $PM_{2.5}$–O_3 interactions

5.6. Future Directions for Intelligent, Adaptive, and Data-Driven Governance

Moving towards intelligent, adaptive, data-driven regional atmospheric governance will be essential in the future [67]. Traditional governance tends to focus on periodic planning, the setting of targets for the upcoming year(s), and an evaluation at the end of the year. Although these tools are still relevant, they are not sufficient to effectively address dynamic $PM_{2.5}$–O_3 interactions. The conditions and emissions sources in the atmosphere change quickly, as do industrial activities and human exposure. Governance pathways need to be continually modified in light of real-time evidence.

High-resolution monitoring networks are key to this shift. Information on pollutant concentrations, precursor distributions, and exposure patterns can be obtained in greater detail from ground-based monitoring, satellite remote sensing, mobile observations, unmanned platforms, and low-cost sensors. These data can be used to enhance air-emission inventories, detect abnormal emissions, monitor pollutant transport, and assess the effectiveness of policies. Enhanced monitoring is particularly required for VOC and NH_3; the lack of data is a limitation to the accurate diagnosis of secondary pollution mechanisms [24].

AI and machine learning (machine learning) help to predict, identify sources, conduct sensitivity analyses, and assess policy impacts. These techniques can reveal nonlinear patterns and stitch together a massive amount of data from monitoring, weather, emissions, traffic, industry, and health care systems. However, data-driven methods should not be used in place of a mechanism-based model. Prediction might be good in purely statistical models, but they may not be adequate for explaining chemical aspects of processes or assessing emission control scenarios under conditions different from the past. The most promising avenue is the coupling between machine learning, atmospheric chemistry, and economic modeling and policy simulation [68].

There is a need for adaptive governance as well. Instead of a list of pathways with predetermined emission reductions, there is a need for policies to incorporate feedback mechanisms that adjust strategies based on observed results. When NO_x is reduced, and O_3 increases, stronger VOC control should be implemented. When nitrate is a major component of $PM_{2.5}$, the coordination of NH_3 and NO_x needs to be enhanced. When regional transport is a major source of local pollution episodes, the extent of joint control should be increased. This adaptive approach enables governance to adjust to the changes in the atmosphere and socio-economic conditions [69].

The use of digital decision-support platforms will enhance further regional cooperation [70]. Data platforms, emission inventories, regional forecasting systems, and policy dashboards can facilitate data sharing and mitigate information asymmetry between jurisdictions. Data governance, however, needs to address data quality control, privacy, institutional accountability, and the need to make data publicly accessible. Governance for intelligence is not an "all things technical" process but is firmly rooted in fairness, accountability, and the public good.

To achieve regional path optimization and governance synergy, we need to move from a fragmented, pollutant-based governance structure to an integrated, mechanism-based, regionally coordinated governance. The best route is not necessarily the one that achieves the largest absolute emissions reduction, but the one that delivers the most total reductions in $PM_{2.5}$, improvements in air quality, reductions in O_3, carbon neutrality, public health benefits, and regional equity within realistic economic and institutional constraints [17]. A regional adaptive optimization model integrating monitoring, modeling, multi-objective decision-making, implementation, and feedback adjustment is shown in **Figure 2**.

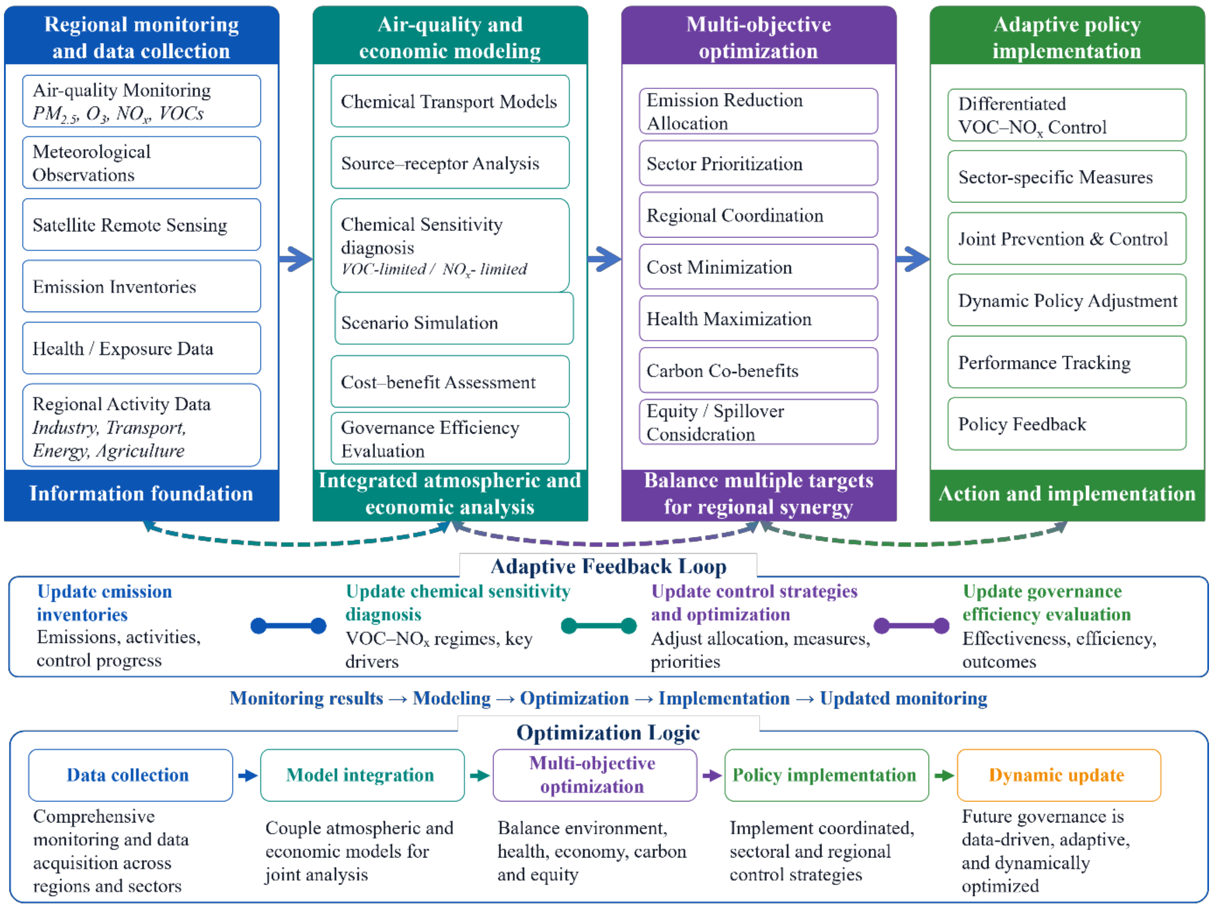

Figure 2. Regional path optimization model for synergistic $PM_{2.5}$–O_3 governance.

6. Conclusion

The regional stage of atmospheric environmental governance has become more complex, with the coordinated control of $PM_{2.5}$ and O_3 becoming more important than the reduction of individual pollutants. Particulate pollution-photochemical pollution interaction is a multidimensional problem of nonlinear atmospheric chemistry, common sources of precursors, regional pollution transport, and evolving socio-economic structures. While many areas have made significant progress in reducing $PM_{2.5}$ through traditional emission-reduction measures, ongoing or worsening O_3 episodes show that such policies are no longer effective. Good governance should, therefore, move towards synergy, mechanisms, and region-based differentiated approaches.

The key messages from this review are that the relationship between $PM_{2.5}$ and O_3 is linked to emissions of their precursors, to O_3 production capacity in the atmosphere, to photolysis, to the nature of heterogeneous reactions, and to meteorological conditions. A decrease in SO_2, NO_x, VOCs, NH_3, and primary particles can result in varying impacts dependent on the local and seasonal chemical sensitivity. Specifically, NO_x reduction will yield benefits for nitrate aerosol reduction in some cases, may also yield benefits for O_3 in VOC-limited cases, and will yield co-benefits for secondary organic aerosol reduction in VOC-limited cases. These interactions show that the reduction of emissions should be based not only on the amount of emissions but also on the type (species) of pollutant, the type of source (category), the chemical regime, and the emission time.

Evaluation of efficiency is an important basis for assessing whether atmospheric governance leads to environmental improvement using reasonable economic, technological, and institutional inputs. Current evaluation methods, however, tend to focus on reducing $PM_{2.5}$ or traditional pollutants and do not adequately account for impacts on O_3, spillovers, health benefits, carbon co-benefits, or equity. New assessment tools should incorporate multi-pollutant metrics, undesirable outputs, source-receptor linkages, exposure-related health impacts, and dynamic considerations of technological innovation. The combined use of DEA, SBM, spatial econometric models, and atmospheric chemical simulations can enhance the diagnostic power of governance efficiency assessments.

Best available paths to emission reductions should be tailored to a region's emission profile and atmospheric sensitivity. Different strategies should be adopted for industrial, power, transport, residential, and agricultural sectors. There is a need for the coordinated management of industrial VOCs, transport NO_x, agricultural NH_3, and combustion primary particles, rather than individual management. Collaborative actions towards long-term mitigation can include structural adjustment, clean energy transition, process optimization, end-of-pipe control, urban planning, and nature-based solutions, which translate into science-based scenario simulation and cost–benefit analysis. It is not necessarily the most absolute emission reduction that will be the most efficient pathway, but rather the one that delivers the greatest integrated benefits for air quality, health, carbon reduction, and regional sustainability.

Regional coordination is critical, as $PM_{2.5}$ pollution and the secondary formation of O_3 often occur across borders. Governance systems need to shift from administrative fragmentation to airshed-based joint prevention and control. Regional cooperation can be enhanced through the allocation of responsibilities, ecological compensation, shared monitoring, unified emission inventories, and coordinated emergency responses. Policy synergy should go beyond air pollution control to encompass carbon neutrality, public health protection, industrial upgrading, and environmental justice.

In general, the implementation of synergistic $PM_{2.5}$–O_3 control is a shift from end-of-pipe pollution control to a system of atmospheric governance. Future studies are needed to further strengthen the coupling among atmospheric chemistry, environmental economics, regional planning, and data-based decision support. Further focus needs to be placed on VOC species profiles, NH_3 control, dynamic O_3 sensitivity, health-risk valuation, and uncertainty analysis. Connecting efficiency evaluation to path optimization can enable more precise, adaptive, equitable, and sustainable regional atmospheric governance.

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References

[1] Fann, N., Risley, D., 2013. The public health context for PM2.5 and ozone air quality trends. Air Quality, Atmosphere & Health. 6(1), 1–11.

[2] Li, Z., Yuan, X., Xi, J., et al., 2021. The objects, agents, and tools of Chinese co-governance on air pollution: A review. Environmental Science and Pollution Research. 28(20), 24972–24991.

[3] Dominici, F., Peng, R.D., Barr, C.D., et al., 2010. Protecting human health from air pollution: shifting

from a single-pollutant to a multipollutant approach. Epidemiology. 21(2), 187–194.

[4] Du, S., He, C., Zhang, L., et al., 2024. Policy implications for synergistic management of PM2.5 and O3 pollution from a pattern-process-sustainability perspective in China. Science of the Total Environment. 916, 170210.

[5] Su, Z., Yang, L.,; Chen, Y., et al., 2024. Analysis of Synergistic Changes in PM2.5 and O3 Concentrations Based on Structural Equation Model Study. Atmosphere. 15(11), 1374.

[6] Zhao, S., Yu, Y., Qin, D., et al., 2019. Analyses of regional pollution and transportation of PM2.5 and ozone in the city clusters of Sichuan Basin, China. Atmospheric Pollution Research. 10(2), 374–385.

[7] Diao, B., Wang, Y., Ding, L., 2026. Cross-regional compensation mechanism based on embodied air pollution, shared responsibility and abatement costs. Environment, Development and Sustainability. 1–35.

[8] Liu, Z., Fang, C., Sun, B., et al., 2023. Governance matters: Urban expansion, environmental regulation, and PM2.5 pollution. Science of the Total Environment. 876, 162788.

[9] Hui, L., Chen, Y., Feng, X., et al., 2025. The critical role of oxygenated volatile organic compounds (OVOCs) in shaping photochemical O3 chemistry and control strategy in a subtropical coastal environment. Atmospheric Chemistry and Physics. 25(24), 18355–18371.

[10] Yang, Y., Xu, H., Yang, X., et al., 2025. Exploring synergistic efficiency of air pollution and carbon reduction and its influencing factors: Insights from China. Resources, Conservation and Recycling. 212, 107973.

[11] Xin, C., Li, J., 2025. The effectiveness of environmental taxes on sectoral economic and governance efficiency in a synergistic perspective of air pollution reduction and carbon mitigation. Journal of Environmental Management. 395, 127973.

[12] Wang, Y., Zhao, Z., Shi, M., et al., 2024. Public environmental concern, government environmental regulation and urban carbon emission reduction—Analyzing the regulating role of green finance and industrial agglomeration. Science of the Total Environment. 924, 171549.

[13] Zhang, W., Wen, L., 2023. Research on the analysis of the coupling coordination degree of Shaanxi's atmospheric ecological governance and urban clean governance based on environmental sustainability. Ecological Indicators. 155, 111068.

[14] Ou, J., Zheng, J., Li, R., et al., 2015. Speciated OVOC and VOC emission inventories and their implications for reactivity-based ozone control strategy in the Pearl River Delta region, China. Science of the Total Environment. 530, 393–402.

[15] Shen, J., Cai, W., Chen, X., et al., 2022. Synergies of carbon neutrality, air pollution control, and health improvement—A case study of China energy interconnection scenario. Global Energy Interconnection. 5(5), 531–542.

[16] Duan, W., Wang, X., Cheng, S., et al., 2022. Regional collaboration to simultaneously mitigate PM2.5 and O3 pollution in Beijing-Tianjin-Hebei and the surrounding area: Multi-model synthesis from multiple data sources. Science of the Total Environment. 820, 153309.

[17] Xu, Y., Zhou, S.-C., Feng, Y.-X., et al., 2024. Global air quality enhancement pathways to health benefits and environmental justice. Journal of Hazardous Materials. 480, 136460.

[18] Behera, S.N., Sharma, M., 2010. Reconstructing primary and secondary components of PM2. 5 composition for an urban atmosphere. Aerosol Science and Technology. 44(11), 983–992.

[19] Cuciureanu, R., Dimitriu, G., 2006. Photochemical reactions in the atmosphere-a source of secondary pollutants. Programming Problems (Special Issue). 2, 682–687.

[20] Shao, M., Yang, J., Wang, J., et al., 2022. Co-occurrence of surface O3, PM2.5 pollution, and tropical cyclones in China. Journal of Geophysical Research: Atmospheres. 127(14), e2021JD036310.

[21] Chaturvedi, S., Kumar, A., Singh, V., et al., 2023. Recent advancement in organic aerosol understanding: A review of their sources, formation, and health impacts. Water, Air, & Soil Pollution. 234(12), 750.

[22] Mahobiya, D., Sarkar, A., Mahilang, M., et al., 2025. Elucidating the Intricacies of Biogenic Secondary Organic Aerosol Formation, Growth, and Environmental Significance: A Comprehensive Analysis. Water, Air, & Soil Pollution. 236(9), 596.

[23] Yin, L., Bai, B., Zhang, B., et al., 2025. Regional-specific trends of PM2.5 and O3 temperature sensitivity in the United States. npj Climate and Atmospheric Science. 8(1), 12.

[24] Jia, C., Yan, G., Yu, X., et al., 2025. Evidence for coordinated control of $PM_{2.5}$ and O_3: long-term observational study in a typical cty of central plains urban agglomeration. Toxics. 13(5).

[25] Li, C., Liu, Y., Cheng, B., et al., 2022. A comprehensive investigation on volatile organic compounds (VOCs) in 2018 in Beijing, China: Characteristics,

sources and behaviours in response to O3 formation. Science of the Total Environment. 806, 150247.
[26] Wang, C., Yan, Y., Niu, Y., et al., 2021. Formation and driving factors of sulfate in PM2.5 at a high-level atmospheric SO2 city of Yangquan in China. Air Quality, Atmosphere & Health. 14(4), 491–501.
[27] Lee, S.-R., Kim, G., 2024. Assessing Ammonia (NH_3) Emissions, Precursor Gas (SO_2, NO_x) Concentrations, and Source Contributions to Atmospheric $PM_{2.5}$ from a Commercial Manure Composting Facility. Applied Sciences. 14, 11467.
[28] Ziemann, P.J., Atkinson, R., 2012. Kinetics, products, and mechanisms of secondary organic aerosol formation. Chemical Society Reviews. 41(19), 6582–6605.
[29] Zhao, F., Wang, Y., Xi, S., 2025. Meteorological Control on Ozone Response to NOx Emission Reduction Events: Evidence From the Spring Festival Periods. Geophysical Research Letters. 52, e2025GL118737.
[30] Mukta, T.A., Hoque, M.M.M., Sarker, M.E., et al., 2020. Seasonal variations of gaseous air pollutants (SO2, NO2, O3, CO) and particulates (PM2.5, PM10) in Gazipur: an industrial city in Bangladesh. Advances in Environmental Technology. 6(4), 195–209.
[31] Bergin, M.S., West, J.J., Keating, T.J., et al., 2005. Regional atmospheric pollution and transboundary air quality management. Annual Review of Environment and Resources. 30, 1–37.
[32] Wang, R., Zhang, N., Wu, J., et al., 2025. Sub-seasonal and Spatial Variations in Ozone Formation and Co-control Potential for Secondary Aerosols in the Guanzhong Basin, Central China. EGUsphere. 1–29.
[33] He, C., Liu, J., Zhou, Y., et al., 2024. Synergistic PM(2.5) and O(3) control to address the emerging global PM(2.5)-O(3) compound pollution challenges. Eco-Environment & Health. 3(3), 325–337.
[34] Yan, J., 2026. Air Quality Evolution Characteristics and Driving Factors in Asian Megacities: A Systematic Review. Applied and Computational Engineering. 216, 134–143.
[35] Cheng, X., Fan, L., Wang, J., 2018. Can energy structure optimization, industrial structure changes, technological improvements, and central and local governance effectively reduce atmospheric pollution in the Beijing–Tianjin–Hebei area in China? Sustainability. 10(3), 644.
[36] Noruzzade, E., Mirzaei, N., Janghorbanian, S., et al., 2025. A systematic global review of fixed air quality monitoring stations: Spatial distribution, typologies, measured pollutants, technologies, regulatory standards, and research gaps. Journal of Air Pollution and Health. 10.
[37] Song, M., An, Q., Zhang, W., et al., 2012. Environmental efficiency evaluation based on data envelopment analysis: A review. Renewable and Sustainable Energy Reviews. 16(7), 4465–4469.
[38] Li, H., Fang, K., Yang, W., et al., 2013. Regional environmental efficiency evaluation in China: Analysis based on the Super-SBM model with undesirable outputs. Mathematical and Computer Modelling. 58(5-6), 1018–1031.
[39] Kortelainen, M., 2008. Dynamic environmental performance analysis: A Malmquist index approach. Ecological Economics. 64(4), 701–715.
[40] Coelho, S., Ferreira, J., Lopes, M., 2023. Source apportionment of air pollution in urban areas: a review of the most suitable source-oriented models. Air Quality, Atmosphere & Health. 16(6), 1185–1194.
[41] Manisalidis, I., Stavropoulou, E., Stavropoulos, A., et al., 2020. Environmental and health impacts of air pollution: a review. Frontiers in Public Health. 8, 14.
[42] Zhang, X., Han, L., Wei, H., et al., 2022. Linking urbanization and air quality together: A review and a perspective on the future sustainable urban development. Journal of Cleaner Production. 346, 130988.
[43] Burger, J., 2022. Trust and consequences: Role of community science, perceptions, values, and environmental justice in risk communication. Risk Analysis. 42(11), 2362–2375.
[44] Sun, B., Wang, M., Zhang, H., et al., 2025. Assessing spatiotemporal trends and drivers of collaborative governance for air quality and carbon emission control: Evidence from typical urban agglomerations in China. Journal of Cleaner Production. 519, 146034.
[45] Wang, L., Lun, X., Wang, Q., et al., 2024. Biogenic volatile organic compounds emissions, atmospheric chemistry, and environmental implications: a review. Environmental Chemistry Letters. 22(6), 3033–3058.
[46] Pisoni, E., Clappier, A., Degraeuwe, B., et al., 2017. Adding spatial flexibility to source-receptor relationships for air quality modeling. Environmental Modelling & Software. 90, 68–77.
[47] Peszko, G., Amann, M., Awe, Y.A., et al., 2023. Air Pollution and Climate Change: From Co-Benefits to Coherent Policies. World Bank Publications: Washington, DC, USA.
[48] Xu, H., Zhang, W., Ren, Y., et al., 2024. Role of primary drivers leading to emission reduction of major air pollutants and CO2 from global power plants. Environment International. 190, 108936.
[49] de Souza, A., de Oliveira-Júnior, J.F., Cardoso, K.R.A., et al., 2025. Impact of vehicular emissions on ozone levels: A comprehensive study of nitric oxide

and ozone interactions in urban areas. Geosystems and Geoenvironment. 4(1), 100348.

[50] Parmar, G.R., Rao, N., 2008. Emerging control technologies for volatile organic compounds. Critical Reviews in Environmental Science and Technology. 39(1), 41–78.

[51] Guo, Y., Zhou, M., Peng, L., et al., 2023. Carbon mitigation and environmental co-benefits of a clean energy transition in China's industrial parks. Environmental Science & Technology. 57(16), 6494–6505.

[52] Kurniawan, T.A., Khan, S., Mohyuddin, A., et al., 2024. Technological solutions for air pollution control to mitigate climate change: an approach to facilitate global transition toward blue sky and net-zero emission. Chemical Papers. 78(12), 6843–6871.

[53] Acemoglu, D., Akcigit, U., Hanley, D., et al., 2016. Transition to clean technology. Journal of Political Economy. 124(1), 52–104.

[54] Alwi, S.R.W., Klemeš, J.J., Varbanov, P.S., 2016. Cleaner energy planning, management and technologies: perspectives of supply-demand side and end-of-pipe management. Journal of Cleaner Production. 136, 1–13.

[55] Karkoszka, T., 2011. Minimization of environmental risk by optimization of the end-of-pipe processes. Journal of Achievements in Materials and Manufacturing Engineering. 49(2), 499–506.

[56] Singh, N., Singh, S., Mall, R., 2020. Urban ecology and human health: implications of urban heat island, air pollution and climate change nexus. In Urban Ecology. Elsevier: Amsterdam, The Netherlands. pp. 317–334.

[57] Deweerdt, T., Fabre, A., 2022. The role of land use planning in urban Transport to Mitigate climate Change: A literature review. Advances in Environmental and Engineering Research. 3(3), 1–22.

[58] Rahmati, Y., 2025. Modeling Biodiversity under Air Pollution with AI: An Integrated Approach to Prediction, Attribution, and Optimization. SSRN. Available from: file:///C:/Users/EDY/Downloads/ssrn-6000074%20(1).pdf

[59] Gao, J., Yuan, Z., Liu, X., et al., 2016. Improving air pollution control policy in China—A perspective based on cost–benefit analysis. Science of the Total Environment. 543, 307–314.

[60] Ren, H., Zhou, W., Nakagami, K., et al., 2010. Multi-objective optimization for the operation of distributed energy systems considering economic and environmental aspects. Applied Energy. 87(12), 3642–3651.

[61] Rautela, K.S., Goyal, M.K., Mohan, M., 2025. A review of extreme air pollution measurement and modeling techniques with applications. Renewable and Sustainable Energy Reviews. 240, 117178.

[62] Bellinson, R., Fabre, A., 2019. Learning pathways and the governance of innovations in urban climate change resilience and adaptation. Journal of Environmental Policy & Planning. 21(1), 76–89.

[63] Obahiagbon, E.G., Kosoe, E.A., 2024. Economic dimensions of air pollution: Cost analysis, valuation, and policy impacts. In Sustainable Strategies for Air Pollution Mitigation: Development, Economics, and Technologies. Springer: Cham, Switzerland. pp. 111–139.

[64] Matthias, V., Arndt, J.A., Aulinger, A., et al., 2018. Modeling emissions for three-dimensional atmospheric chemistry transport models. Journal of the Air & Waste Management Association. 68(8), 763–800.

[65] Marques, A., Rodrigues, J., Lenzen, M., et al., 2012. Income-based environmental responsibility. Ecological Economics. 84, 57–65.

[66] West, J.J., Smith, S.J., Silva, R.A., et al., 2013. Co-benefits of mitigating global greenhouse gas emissions for future air quality and human health. Nature Climate Change. 3(10), 885–889.

[67] Zhu, X., Wang, H., Han, Y., et al., 2025. Reconstructing the VOC–Ozone Research Framework Through a Systematic Review of Observation and Modeling. Sustainability. 17(16), 7512.

[68] Ma, J., Ding, Y., Cheng, J.C.P., et al., 2020. Identification of high impact factors of air quality on a national scale using big data and machine learning techniques. Journal of Cleaner Production. 244, 118955.

[69] Plummer, R., Armitage, D., 2010. Integrating perspectives on adaptive capacity and environmental governance. In Adaptive Capacity and Environmental Governance. Springer: Cham, Switzerland. pp. 1–19.

[70] Pandey, A., Choubey, V., 2025. Data-driven approach for measuring and curbing Green House Gases (GHG) emissions in the supply chain of India. Journal of Cleaner Production. 504, 145392.