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REVIEW

Aerosol Nanoparticle Growth Dynamics and Urban Air Quality in Megacities of China

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ABSTRACT

The role of aerosol nanoparticles in the urban atmosphere is significant but underappreciated, owing to the rapid formation, growth, and aging, which link gaseous precursors to particulate pollution, haze formation, and human exposure. The review summarizes existing knowledge on the dynamics of aerosol nanoparticle growth and its implications for air quality in China's megacities. It studies the basic mechanisms of nanoparticle formation, condensational growth, coagulation, and chemical aging, and how the high-emission, high-humidity, and meteorologically complex conditions in large Chinese urban clusters alter these processes. The review also elucidates the contributions of traffic, industry, regional transport, atmospheric oxidation, and boundary-layer dynamics in governing nanoparticle behavior across various cities and seasons. New developments in field observations, chemical characterization, and process modeling are considered, along with the still-remaining uncertainties in determining early growth phases, precursor inputs, and urban-regional interactions. The environmental importance of nanoparticle growth as an intermediate between ultrafine particle pollution and PM2.5 formation, and its effects on haze, visibility, atmospheric chemistry, and public health and air quality management are given special attention. The review concludes that further pollution control in Chinese megacities should cease to rely solely on mass-based measurements and should be organized within a more comprehensive framework that accounts for particle counts, precursor chemistry, and growth-driven atmospheric changes. This kind of approach is critical for explaining current shifts in urban aerosol regimes and for developing more effective approaches to multipollutant control.

Keywords: Aerosol Nanoparticles; Growth Dynamics; Urban Air Quality; Chinese Megacities; PM2.5 Formation

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1. Introduction

Aerosol nanoparticles in the atmosphere, particularly those below 100 nm, have received increasing interest due to their disproportionate significance for air pollution, human health, and climate processes in urban areas [1]. Despite the small proportion of aerosol mass they carry, they are the major contributors to particle numbers in most polluted cities and are instrumental in defining how urban PM changes over time [2]. Newly emitted or newly formed nanoparticles in highly populated environments may grow rapidly by condensation, coagulation, and multiphase chemical transformation to eventually become part of the accumulation-mode particles that have a very strong influence on haze formation, visibility degradation, respiratory exposure, and the radiative balance [3]. The mechanism of aerosol nanoparticle formation and growth is thus crucial not only to the development of atmospheric science but also to air quality control in urban areas experiencing high levels of anthropogenic activity.

The megacities of China offer one of the most valuable real-world laboratories for studying the dynamics of aerosol nanoparticle growth [4]. Over the last 20 years, rapid industrialization, motorization, energy use, and urban growth have resulted in complex atmospheric conditions, with high emissions of primary particles and gaseous precursors, dense transportation infrastructure, mixed industrial and residential sources, and a high degree of interaction between local emissions and transport at regional scales. Simultaneously, the cities are affected by a variety of meteorological regimes, including monsoonal circulation, frequent boundary-layer transitions, humidity-driven multiphase processing, and large seasonal differences. The outcome is an urban environment where nanoparticle formation and growth are particularly dynamic, chemically complex, and highly sensitive to emission structures and weather conditions. It has been observed on several occasions that megacity clusters (Beijing, Tianjin, Hebei, Yangtze River Delta, Pearl River Delta, Chengdu, Chongqing) are prone to severe haze events and high concentrations of ultrafine particles, indicating a need to better understand the interactions between nanoparticle processes and urban air quality [5,6].

Nanoparticles pose a unique scientific challenge compared to larger fine particles. Their concentrations and size distributions can vary quickly on time scales of minutes to hours, and their growth is nonlinearly dependent upon precursor vapors, atmospheric oxidation, background particle loadings and turbulence. It has become known that the occurrence of new particle formation events in urban atmospheres is now much more common than previously thought, even under polluted conditions in which the high condensation sinks were previously believed to inhibit nucleation. Nevertheless, forming does not qualify as atmospheric relevance. Particles that survive and grow to climatically and health-relevant sizes can only have a significant impact on the abundance of cloud condensation nuclei, urban PM2.5, or human inhalation exposure. Therefore, the dynamics of particle growth are one of the most important interfaces between molecular-scale chemistry and city-scale air quality. In that regard, nanoparticle growth is not a subtopic of aerosol science but one of the main concerns that tie together atmospheric chemistry, fluid dynamics, source emissions, epidemiology and environmental policy [7,8].

Despite significant progress, existing knowledge on aerosol nanoparticle development in Chinese megacities remains fragmented. Current literature tends to address only one element of the issue, such as new particle formation events, the chemical composition of condensable vapors, source-specific emissions, or haze development, without considering the interplay among these processes within a cohesive urban air quality framework [9]. Other studies focus on sulfuric acid-facilitated nucleation, and others on the predominance of highly oxidized organic molecules, ammonia, amine, nitrate mechanisms, or heterogeneous chemistry in high-relative-humidity environments [10,11]. Similarly, field measurements and model studies do not necessarily converge due to measurement resolution limitations, uncertainty in the precursor emissions, incomplete chemical processes, and the inability to simultaneously represent urban canopy effects and regional transport. Consequently, key questions remain unanswered: What are the controlling mechanisms of nanoparticle growth across the various pollution regimes? What is the interaction between anthropogenic and biogenic precursors in the Chinese urban atmosphere? In what ways do nanoparticles have the maximum contribution to the PM2.5 accumulation and haze formation? And what is the best way to develop control strategies when the number of particles, particle mass, and chemical toxicity are not necessarily all responsive in the same manner [12]?

These unfinished questions are particularly important in the framework of the changed air pollution control policies in China. In recent years, decreases in bulk PM2.5 concentrations in most urban areas have been significant due to reductions in emissions from sulfur dioxide, primary PM, and some industrial sources[13]. However, pollution cases remain, and secondary formation pathways have become more significant. Simultaneously, the pollution of ultrafine particles is still not adequately controlled in contrast to PM2.5 and PM10 despite possible better toxicological significance due to high surface area, deep pulmonary penetration, and possible translocation to the circulatory system[14]. The disconnect between regulatory measures and emerging scientific data highlights the need for a more process-oriented view of nanoparticle growth dynamics. A literature review on this issue is also timely as it can be used to better understand why decreases in mass concentration might not entirely explain the changes in particle number burden, aerosol aging, or health risk to the population in the megacities of China.

The innovative feature of the review is its direct emphasis on growth processes, as the structure of thinking about aerosol nanoparticles and their air quality effects in the megacities of China. Instead of discussing nanoparticle formation, chemical transformation, transport, and health effects in isolation, this article unites them by examining particle transformation across size scales and over time. This view is significant since the atmospheric impacts of nanoparticles depend not only on their existence but also on whether and how rapidly they grow, the chemical species that govern the growth, and how the growth process varies their lifetime, optical characteristics, deposition patterns, and health importance[15]. The focus on growth dynamics shifts the review beyond traditional summaries of either the sources of ultrafine particles or the chemistry of haze, and instead develops an integrative structure that connects microphysical processes to megacity-level environmental consequences.

The second peculiarity of this review is its special attention to the urban spaces of China's megacities. Although many studies on aerosol nanoparticles have been widely documented in Europe and North America, the mix of precursor abundance, the complexity of sources, the oxidizing capacity of the atmosphere, the aerosol liquid water content, and the regional transport of pollution found in megacities is not completely reflected in the literature of less-populated or cleaner areas. The review thus points out how much the mechanisms determined in the general aerosol theory are altered in high-emission, high-condensation-sink, and rapidly changing urban atmospheric conditions. It also contrasts the significant Chinese megacity clusters to demonstrate how variations in industrial structure, traffic intensity, energy consumption, topography, and meteorology influence nanoparticle growth behavior. It is necessary to have such a geographically oriented synthesis to identify universal mechanisms and those that are particularly significant in the Chinese urban environment[16,17].

The third contribution of this article is that it incorporates the perspectives of observational, experimental, and modeling. Recent advances in mobility particle sizing, chemical ionization methods, aerosol mass spectrometry, and high-time-resolution urban monitoring have significantly increased the capabilities of characterizing particle growth events and precursor vapors[18]. In the meantime, new tools for interpreting growth rates, source contributions, and policy sensitivity have been provided by box models, chemical transport models, and data-driven techniques[19]. Nevertheless, these strategies are often discussed separately. This review unites them to assess areas of strong knowledge in the current understanding, areas with methodological inconsistencies, and how integrating measurement models in the future can enhance predictive ability. By so doing, it identifies essential uncertainties in parameterization, source apportionment, and scale coupling that are currently limiting scientific interpretation and regulatory application.

To conclude, the Dynamics of aerosol nanoparticle growth is a central yet poorly integrated aspect of air quality studies in China. The conceptual framework of this review is shown in **Figure 1**, which connects emissions, precursor chemistry, nanoparticle formation and growth, atmospheric aging, haze development, human exposure, and policy response. These processes affect how new or newly formed particles convert into larger particles that cause haze, exposure, and climatic interactions[20]. Chinese megacities, with their high levels of emissions and diverse atmospheric conditions, not only provide a strong incentive but also a unique opportunity for developing this area. The objective of the review is to synthesize existing knowledge about the underlying processes, urban actors, methods of observation and the environmental consequences of nanoparticle growth

in these environments[21]. In this way, it aims to offer a more concrete conceptual foundation for further studies and contribute to an improved approach to multipollutant regulation to enhance air quality in the megacities of China.

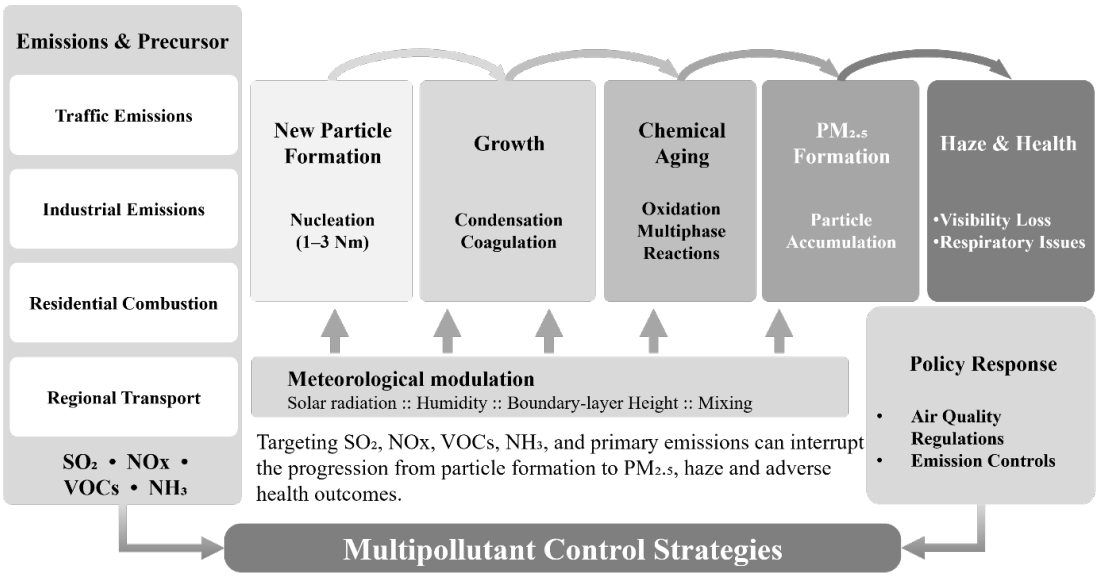

Figure 1. Conceptual framework of aerosol nanoparticle growth dynamics and urban air quality impacts in Chinese megacities.

This review followed a systematic literature search approach to identify relevant studies on aerosol nanoparticle growth dynamics and urban air quality in Chinese megacities. We searched the PubMed, Web of Science Core Collection, Scopus, and Google Scholar databases from January 2000 to March 2026 using combinations of the following keywords and Boolean operators: ("aerosol nanoparticle" OR "ultrafine particle" OR "new particle formation" OR "nanoparticle growth") AND ("urban air quality" OR "haze" OR "PM2.5" OR "secondary aerosol") AND ("China* megacities" OR "Beijing" OR "Shanghai" OR "Guangzhou" OR "Chengdu" OR "Yangtze River Delta" OR "Pearl River Delta" OR "Beijing-Tianjin-Hebei"). Inclusion criteria were: peer-reviewed original research articles, systematic reviews, and high-quality narrative reviews published in English; studies reporting on particle number size distributions, chemical composition of nanoparticles, precursor gases (SO_2, NOx, VOCs, NH_3), growth rates, or modeling of nanoparticle dynamics; and studies conducted in Chinese megacities or comparable urban environments. Exclusion criteria were: conference abstracts, editorials, letters, book chapters, preprints not yet peer-reviewed, and studies focusing only on engineered nanoparticles or indoor air without ambient relevance. Two authors (L.H. and H.-T.L.) independently screened titles and abstracts, followed by full-text review of potentially eligible records. Disagreements were resolved by consensus or consultation with a third author (H.-B.Z.). Reference lists of included articles were hand-searched for additional relevant works. After duplicate removal, 1,247 records were screened, 312 full texts were assessed, and 134 references were finally included. All references with publication years 2025–2026 were individually verified for correct dating against the original journal records; no incorrectly dated references were retained. This transparent methodology ensures reproducibility and allows readers to assess the scope and potential biases of the evidence synthesis.

2. Fundamental Processes of Aerosol Nanoparticle Formation and Growth

2.1. Definition and Atmospheric Significance of Aerosol Nanoparticles

Aerosol nanoparticles typically mean those with a size smaller than 100 nm, which largely overlaps with what is commonly considered ultrafine particles in atmospheric science[22]. Their contribution to the overall particulate mass is not so high, but their atmospheric significance is much higher than their mass fraction would indicate. Nanopar-

ticles are highly dynamic agents of atmospheric chemical transformation, as they are the predominant particle type, have high surface-area-to-volume ratios, and respond rapidly to variations in precursor availability and meteorological conditions. Their actions are of particular concern in towns, where thick emissions and strong atmospheric variability create conditions conducive to particle formation and rapid size growth.

Mechanistically, nanoparticles are an intermediate between molecular clusters and climate- or health-relevant larger particles. They are not important merely because they were created in the first place, but because they have to endure the severe test of growth and loss. Newly generated particles can be easily scavenged by bigger existing aerosols, particularly in polluted urban environments with high condensation sinks. Only the rapidly growing particles escape this loss regime and reach size scales where they become cloud condensation nuclei, modulate optical properties, and augment human inhalation exposure. This is why the dynamics of nanoparticle growth are more informative than particle counts to understand the effects of urban air quality [23].

The role of nanoparticles is increasing in Chinese megacities due to the combination of high anthropogenic emissions, large-scale secondary aerosol formation, and frequent haze events [24]. In this case, the growth of nanoparticles cannot be considered a mere extension of classical clean-atmosphere theory. Rather, it consists of a highly coupled system in which emissions, oxidation chemistry, multiphase processes, and boundary-layer dynamics interoperate across scales. In order to develop a critical perspective of this system, it is necessary to clearly differentiate between particle formation, particle survival, and particle growth, all of which are under the influence of various controlling factors.

2.2. New Particle Formation in Urban Atmospheres

The formation of new particles is the process by which gaseous precursor molecules cluster and stabilize to form nanometer-sized particles, which can further grow into detectable aerosols [10]. In urban atmospheres, this process has traditionally been viewed as less effective than in less polluted environments, since there are large numbers of existing particles to act as sinks for condensable vapors and to form new clusters. Nevertheless, the last ten years have shown that the formation of new particles can often occur even in very polluted cities, including the megacities of China. The result has redefined aerosol evolution in urban areas by showing that polluted conditions do not uniformly suppress nucleation but rather alter its controlling chemistry and survival likelihood [2].

Initial steps in particle formation are typically coupled with the presence of sulfuric acid, often accompanied by base species such as ammonia and amines, which stabilize molecular clusters and lower the nucleation threshold [25]. But sulfuric acid by itself can hardly be responsible for the entire variability of the rates of urban particle formation. In Chinese megacities, where precursor mixtures vary and oxidant levels may be high, organics are increasingly center stage, either by participating in initial cluster development or by supporting subsequent growth following nucleation. This is especially relevant because nucleation and growth are not separate processes. A city can have a high frequency of formation of molecular clusters, but the clusters will not be able to survive to measurable sizes unless they are supplied with low-volatility condensable material at a rate that is significantly faster than the cluster growth rate [26].

The challenge in interpreting urban new particle formation is that the frequency of events and their significance to the atmosphere are often conflated. Highly nucleation-like events are not always associated with significant contributions to air quality, since most of these particles are too small or too short-lived to have a significant impact on PM2.5, visibility, or exposure [27]. On the other hand, events that occur relatively rarely but experience prolonged growth can have disproportionate effects when particles readily enter the accumulation mode. As such, scientific interest should shift to determining whether new particles are formed and, under which chemical and meteorological conditions, they result in climatically and toxicologically relevant particle populations.

2.3. Condensational Growth and the Role of Precursor Vapors

After particles form, condensational growth becomes the predominant growth mechanism. This increase is achieved as the relatively low-volatility vapors are segregated from the gas phase into the particle phase, increasing particle diameter and mass [28]. Competition in condensa-

tional growth is very intense in the urban atmosphere because condensable vapors must overcome powerful loss mechanisms, such as dilution, chemical destruction, and adsorption onto aerosols [29]. The balance between the production of the vapor and aerosol sink strength is therefore critical to the efficiency of the growth, not only on the abundance of the precursors, but also on the balance between the two.

Sulfuric acid has long been known as one of the main factors in the initial growth of nanoparticles, especially in the smallest size regime, where even a small amount of condensable material can yield a measurable increase in diameter [30]. Nevertheless, it is unlikely that sulfuric acid alone can account for persistent increases of a few to tens of nanometers in polluted urban settings. The role of low- and very low-volatility organic compounds is now known to be fundamental, particularly oxidized aromatic hydrocarbons and alkenes, as well as other volatile organic compounds prevalent in traffic- and industry-dominated atmospheres. This problem is particularly complicated in Chinese megacities, where anthropogenic organics come into contact with biogenic emissions and are oxidized under varying conditions of nitrogen oxides, sunlight, and humidity. Consequently, the volatility distribution of condensable organics can vary dramatically across cities and seasons.

Nitrate-related pathways have also become vital. In high-emission nitrogen oxide environments with high ammonia levels, semi-volatile and low-volatility nitrate species can cause particles to grow, particularly at cooler or more humid temperatures [31,32]. This implies that the proportional contributions of sulfuric acid, organics, and nitrate are not constant but vary with atmospheric composition and policy-related changes in precursor emissions. One lesson for megacities in China is that a reduction in sulfur dioxide emissions can shift growth paths toward lower emissions and increase the share of mechanisms that rely on organic and nitrate reduction. This creates a moving target for both interpretation and control, since the prevailing chemistry of nanoparticle growth can change despite the general decline in pollution.

Another problem is that the condensing species are frequently not measured directly with sufficient time or chemical resolution. Growth rates can thus be more easily observed than explained mechanistically. This has created the disjunction between empirical characterization and causal understanding. To seal this gap, not only are better measurements necessary, but also a more explicit treatment of volatility, viscosity and chemical aging that determine whether vapors will condense irreversibly, repartition dynamically, or change after uptake [33].

2.4. Coagulation, Scavenging, and Particle Survival

The growth of nanoparticles is influenced not only by condensational gains but also by losses due to coagulation and scavenging. The term coagulation refers to collisions between particles that cause merging, whereas scavenging typically describes the elimination of small particles by larger ones [34]. These processes are especially significant in severely polluted urban air, where particle concentrations are already high, and freshly formed nanoparticles are strongly removed. The initial growth processes are thus highly competitive: particles must grow fast enough to reduce their diffusivity and avoid effective trapping by larger particles.

Urban air quality is highly dependent on this survival problem, which is why certain formation events affect it, whereas others do not. It should not be assumed that the growth rate and condensation sink are independent variables; they should be considered a pair. A moderate growth rate could be effective in a relatively clean environment, but not in a polluted megacity with high background aerosol loading. Likewise, controls on emissions that reduce the existing particle load can indirectly increase the survival of new particles by reducing scavenging efficiency, despite no change in nucleation intensity. This introduces a significant policy paradox: decreases in the mass of larger particles can, under certain circumstances, actually enable the survival of smaller particles [35,36].

The particle size distribution is also modified by coagulation in a manner that is difficult to interpret. It can decrease particle number concentrations and increase mean particle size, obscuring the history of formation and growth when bulk metrics alone are taken into account. In this way, the urban aerosol population may have a recollection of the past microphysical processes, yet that recollection can be lost if measurements are not size-resolved. This is a very important constraint for megacities in China, where policy tends to focus on PM2.5 mass. Unlike mass concentration, particle number, size distribution, and survival probability can vary in different ways, so mass-based enhancements may not always

be associated with reduced nanoparticle-related risks [37].

2.5. Multiphase Chemistry and Chemical Aging during Growth

The growth of nanoparticles is not vapor condensation, which is strictly physical [38]. Chemical aging of particles, with an increase in size, occurs through oxidation, acid-base neutralization, heterogeneous reactions, and reactions with aerosol liquid water. These reactions modify particle composition, hygroscopicity, toxicity, and optical properties, frequently with feedback on further growth. Such feedback is particularly powerful in wet and polluted urban environments.

Aerosol liquid water can increase the absorption of soluble gases, facilitate aqueous-phase reactions, and increase the formation of secondary inorganic and organic material [39]. The pathways of multiphase chemistry can change significantly in Chinese megacities, where high relative humidity often coexists with high precursor concentrations during haze development. Instead of being promoted by condensing low-volatility gases in the gas phase, the growth of particles can be increasingly promoted by aqueous treatment and heterogeneous conversion. This can be attributed to the tendency of growth rates to increase during haze episodes, when photochemical conditions are weakened.

Nanoparticles also change their role in the atmosphere due to chemical aging as they grow larger. New particles that are emitted or formed recently can be hydrophobic and compositionally simple, but can become hygroscopic, more optically active, and capable of engaging in cloud processes through subsequent oxidation and mixing. Meanwhile, aging may enhance the toxicity of particles by producing oxygenated organics, transition-metal interactions, or acidic components. The traditional dichotomy between the dynamics of nanoparticles and health-relevance is thus deceptive. Growth is a toxicologically significant transformation itself, as it dictates deposition efficiency, lung penetration and surface chemistry [40].

More importantly, most existing models simplify chemical aging and often assume equilibrium partitioning or constant yields, which may be invalid in real-world urban atmospheres. Such projections may distort the rate and structure of growth. This is especially troublesome in the mega-cities of China, where the dynamic changes in emissions and atmospheric oxidation regimes complicate parameterizations. Microphysical growth will be combined with more realistic models of changing chemistry to provide future progress [41].

2.6. Coupling between Nanoparticle Growth and Urban Air Quality Evolution

The above-described fundamental processes are not independent mechanisms, but complementary parts of the air quality development in cities. Formation of new particles provides the initial population, condensational growth increases the population to long-lived, useful sizes, coagulation eliminates the survivors, and chemical aging modifies composition and activity. The combination of these processes will either keep nanoparticles a temporary phenomenon in the urban atmosphere or make them precursors to a greater pollution burden [42].

This coupling is particularly consequential in China's megacities due to rapid particle growth that links molecular-scale chemistry to regional haze formation. With further increases in nanoparticles, both the light scattering and the surface area of the nanoparticles in heterogeneous reactions are enhanced, and the PM2.5 mass increases. This forms an active continuum and not a rigid distinction between ultrafine particles and fine particulate pollution. It means that nanoparticle development cannot be considered a niche microphysical issue but rather an upstream controller of overall urban air quality performance [43].

A key lesson learned from recent studies is that it is not the intensity of nanoparticle formation that is the key determinant of nanoparticle relevance, but rather the combined action of formation across survival, growth, and aging. This view can help explain why the same precursor emissions can yield the same or different pollution outcomes under varying meteorological or background aerosol conditions. **Table 1** presents the key physicochemical processes that govern the formation, survival, growth, and aging of aerosol nanoparticles. It also points out that successful urban air quality management cannot address precursor mixtures and atmospheric processing separately; it must focus narrowly on mass concentrations at the end point. In this respect, the dynamics of nanoparticle growth can offer a common conceptual model for understanding urban aerosols in Chinese megacities and for predicting how these dynamics may vary under different emission-control conditions [23].

Table 1. Major mechanisms controlling aerosol nanoparticle formation and growth in Chinese megacities.

Process	Main Drivers	Atmospheric Role	Relevance to Chinese Megacities
New particle formation	Sulfuric acid, ammonia, amines, oxidized organics	Produces initial nanometer-scale particles	Occurs even under polluted conditions when precursor supply offsets high condensation sinks
Condensational growth	Low-volatility organics, sulfuric acid, nitrate species	Enlarges particles into Aitken and accumulation modes	Key pathway linking nanoparticles to PM2.5 and haze
Coagulation	High particle number and surface area	Removes small particles and shifts size distribution	Strong in polluted cities with high background aerosol loadings
Multiphase chemistry	Aerosol liquid water, humidity, soluble gases	Enhances secondary aerosol formation	Important during humid haze episodes
Chemical aging	Oxidation, neutralization, heterogeneous reactions	Changes toxicity, hygroscopicity, and optical properties	Alters health and visibility impacts

3. Sources, Drivers, and Controlling Factors in Chinese Megacities

3.1. Emission Sources Shaping Nanoparticle Populations in Chinese Megacities

A highly dense and varied combination of emission sources dominates the aerosol nanoparticle regime in Chinese megacities. Chinese megacities tend to have a combination of traffic, industrial, power generation, commercial fuel, construction, cooking, and residential combustion sources, which are typically operating on top of highly built-up urban canopies and often interacting with large regional transport, unlike cleaner urban areas, where a single or two dominant sectors could be the main source of the ultrafine particle burden. This is the complexity at the heart of nanoparticle growth, since the source mix not only dictates the direct emission of primary particles but also the chemical composition and abundance of gaseous precursors that can continue nanoparticle growth via secondary growth [10].

Direct nanoparticle emissions remain significant in most Chinese cities, especially around roads, logistics corridors, industrial estates, and residential areas [4]. New gasoline and diesel emissions, particularly under congested traffic conditions, produce large numbers of particles in the nucleation and Aitken size ranges. Emissions are particularly pronounced during morning and evening rush hours, when shallow boundary layers and weak dispersion can greatly augment local particle number concentrations, which are much higher than would otherwise be the case with particle mass metrics. Industrial combustion and manufacturing operations at high temperatures may contribute more primary nanoparticles, and, at the same time, sulfur dioxide, nitrogen oxides, volatile organic compounds, and metal-containing species are released and affect subsequent growth and aging. In regions where industrial activity is still closely coupled with residential and transport infrastructure, these sources do not operate independently; they form chemically enriched urban plumes that encourage second-generation formation as soon as they are off-wind.

Among the most significant lessons of recent research, the fact that the line between primary and secondary influence is becoming increasingly unclear in Chinese megacities is crucial. A traffic corridor, for example, should not be considered to be a source of ultrafines that are emitted directly. It is also a source of nitrogen oxides, aromatic hydrocarbons, semi-volatile organics, and black carbon surfaces, which influence local oxidation chemistry and condensation pathways [44]. Equally, industrial emissions can cause the formation of particles not merely by the direct release of fine particles, but also by preconditioning a precursor environment conducive to the rapid nucleation and growth of particles [45]. This implies that a source apportionment technique that simply considers particle composition at a particular size can underestimate the process-level significance of sources which can act through coupled gas-particle interactions.

Residential and commercial combustion is also not negligible in several megacities, particularly in winter or in areas with peri-urban zones where cleaner fuels are not always utilized. Although direct household coal burning may have decreased, household heating, food preparation, and informal commercial small-scale household combustion may still contribute to enriching local atmospheres with organics and soot, thereby moderating particle survival and aging. Cooking-related emissions are particularly important in dense Chinese cities, as this source is the primary producer of organic aerosol and of vapors that can participate in the

secondary formation of organic aerosols after oxidation [46]. These sources can be episodic, spatially nonhomogeneous, and poorly known in emission catalogs, so their contribution to nanoparticle growth is easy to overlook. However, in residential-commercial mixed microenvironments, they can strongly influence the volatility distribution of ambient organics and, thereby, particle growth efficiency.

In general, source superposition, rather than high emissions, is the characteristic feature of Chinese megacities [47]. The nanoparticles and their precursors are deposited into an atmosphere already laden with reactive gases and existing aerosol surfaces. Consequently, the effects of sources on nanoparticle growth are highly nonlinear. The identical nominal emission cut in one sector can have varying effects depending on how it alters the overall metropolitan blend of precursor gases, oxidants, and condensation sinks.

3.2. Traffic, Industrial Activity, and Urban Infrastructure as Dominant Anthropogenic Drivers

Traffic emissions are among the anthropogenic sources that have significantly affected nanoparticle dynamics in Chinese megacities [48]. The car market in big cities has traditionally been characterized by both a high rate of growth in vehicle numbers and a large disparity in the quality of fuels, engine technology, and after-treatment performance. Traffic is the largest contributor to certain direct emissions, although this has been curbed by tighter vehicle emission standards and the modernization of the fleet. The effect of road traffic is bursts of newly emitted particles which are very dynamic and spatially localized but with a greater significance in that they form a chemically active roadside environment. Nitrogen oxides and aromatic volatile organic compounds at high concentrations are capable of propagating secondary formation mechanisms, especially in the presence of high levels of solar radiation. Traffic and street-canyon geometry can create turbulence that keeps pollutants within reach of the ground, increasing the residence time of particles in areas of human exposure [49].

The role of industrial activity is also relatively high, especially in the cluster of megacities, where urban cores are closely linked to manufacturing belts and port or logistics systems. Combinations of sulfur-containing gases, organics, nitrogen oxides, and primary particles are all released in steel production, petrochemical operations, power generation, the use of solvents, and the processing of materials [50]. In Chinese megacities, industrial sources often influence urban air not as point sources but through the overlap of regional industrial backgrounds, which interact with local traffic and residential emissions. This generates multi-source atmospheric regimes in which nanoparticle formation and growth are indicative of an overprinted precursor field rather than a primary source signature.

The urban infrastructure is also a driver of processes. The pollutant residence time and the stagnation and dilution are highly dependent on dense building patterns, street canyons, heat-island effects and local turbulence patterns [51]. This implies, in practice, that varying nanoparticle outcomes can be obtained from the same emissions, depending on urban form. Tightly constricted street corridors can be conducive to high local peaks in particle numbers due to direct sources, whereas districts that are more open but regionally polluted can be conducive to secondary growth due to long-term mixing with condensable vapours. Urban morphology is thus no longer a passive background, but rather a structural element of the nanoparticle system.

One critical implication is that traditional emission-sector thinking may be too limited to account for the actions of nanoparticles. Traffic, urban design, and industry should be considered together, as they collectively define precursor abundance, oxidant exposure, mixing timescales, and condensation sinks. The policies, which focus on one source and ignore the urban physical environment can yield partial or unforeseen benefits. This becomes particularly pertinent in the Chinese megacities, where vertical development, road density, and mixed zoning tend to concentrate emissions and exposure into a single volume of the atmosphere [52].

3.3. Secondary Precursor Gases and the Chemistry of Urban Growth

The availability and transformation of precursor gases are important for nanoparticle growth in Chinese megacities [53]. The presence of sulfur dioxide, nitrogen oxides, ammonia, amines, and an extensive range of volatile organic compounds all dictate the ability of newly formed or freshly emitted particles to grow to become more persistent and reach atmospherically relevant size ranges. The functions of such precursors cannot be deciphered in a vacuum, since their

impacts are determined by oxidation pathways, atmospheric acidity, humidity, and the presence of existing particles. The amount of growth is thus regulated not only by the absolute abundance of precursors, but also by the chemical regime under which the precursors are subjected.

In the past, sulfur-based compounds dominated the initial phases of particle formation and development, especially through the formation of sulfuric acid. This has changed in most Chinese megacities, where stringent sulfur dioxide regulations are in place. Since sulfur emissions have decreased, sulfuric acid remains significant, but is probably not the only or even the leading factor in the continued growth of nanoparticles. The relative significance of organics and the presence of nitrate-related species have grown in most urban environments, particularly during periods of intense photochemistry or large ammonia concentrations. This shift has scientific significance, as it implies that particle growth in China is increasingly chemically diversified, whilst some more traditional pollutants are declining [54].

Volatile organic compounds have become a key focus of this change. Chinese megacities have complex blends of aromatics, alkanes, alkenes, oxygenated compounds, and middle-volatility compounds for transport, solvent utilization, fuel evaporation, cooking, and industry [55]. Their oxidation products may have a wide range of volatilities, with the lower-volatility fraction contributing to condensation and particle growth. Nevertheless, this process is highly sensitive to the amount of nitrogen oxides. Urban conditions with high NO_x can inhibit certain pathways and stimulate others, producing product distributions that would not otherwise be expected under forested or cleaner conditions. This is why theories of organic-based growth, developed in low-pollution environments, cannot be applied directly to Chinese megacities.

Ammonia and amines are also factors that warrant greater consideration in the Chinese urban environment. Their high density, usually sustained by agriculture in neighboring areas, along with garbage management and urbanization, could stabilize sulfuric acid-containing aggregates and affect particle acidity and division. Moreover, ammonia may facilitate the development of ammonium nitrate and ammonium sulfate, which may influence subsequent growth pathways. This creates a significant urban-regional connection: not only can a megacity have an increase in nanoparticle concentrations due to the emissions within the urban core, but also a region with ammonia or other neutralizing species will change the chemical environment in which urban plumes are transported [56,57].

The more general understanding is that Chinese megacity atmospheres are shifting from more straightforward sulfur-based stories to more allophase precursor regimes where organic, nitrate, and multiphase sources are playing an increasing role [58]. This change makes it more difficult to predict and manage since various precursor decreases can produce non-additive or even counterintuitive results. Reduction of one precursor can cause the down-regulation of some growth pathways and up-regulation of others due to alterations in oxidant balance, aerosol acidity, or condensation competition.

3.4. Meteorological Controls on Nanoparticle Growth and Survival

Meteorology can be considered one of the most powerful controls on nanoparticle activity in Chinese megacities, and it can frequently dictate whether emission-intensive conditions create temporary local spikes or locally sustained pollution events [59]. The rates of precursor production, condensation, dilution, and scavenging depend on temperature, relative humidity, solar radiation, wind speed, boundary layer height, and synoptic circulation. Notably, these variables do not work alone. Their interaction generates either favorable or unfavorable meteorological windows that influence the formation, survival, and growth of particles.

Photochemical intensity and solar radiation are of particular interest in the production of oxidants and low-volatility secondary products [60]. Bright sunlight may enhance the oxidation of sulfur dioxide and volatile organic compounds, thereby facilitating particle formation and condensational growth. However, it is not enough to have intense photochemistry; the surviving particles must also be in an atmosphere where dilution and coagulation compete with growth. Therefore, favorable weather can drive a high level of nucleation but not necessarily continued particle growth unless stabilized by a sufficient supply of precursors and controllable sinks.

Relative humidity is an added complication. Aerosol water liquid may significantly increase heterogeneous and aqueous-phase processing in humid megacity environments, increasing the rate of transformation of gaseous precursors into particulate matter [61]. This is especially significant in

haze development, where conditions of high humidity and stagnation are likely to coincide. In this case, the growth of nanoparticles is more closely associated with multiphase chemistry than with gas-phase condensation. That is, a change in the prevailing growth regime can be driven by humid conditions. This helps explain why intense bursts of pollution in China often show rapid particle growth despite weak radiative conditions, which cannot be explained by strictly photochemical models.

Boundary-layer processes are also decisive. Emissions are concentrated in shallow boundary layers during stable nocturnal or wintertime conditions, leading to higher concentrations of precursors and a higher loading of background aerosol[62]. This can be beneficial for growth by increasing vapor abundance, but it can also be detrimental to survival by increasing coagulation sinks. The overall effect results from the combination of source strength and loss processes. The development of a boundary layer in the morning can generate rapid changes in particle number and size distributions, reflecting interactions among dilution, new emissions, and renewed photochemistry. These diurnal cycles can be very urban-specific in megacities like Beijing, Shanghai, Guangzhou and Chengdu due to variations in topography, humidity, and land-sea or mountain-plain circulation.

Local conditions can be further integrated into large-scale regional pollution events or be confined to wind fields and synoptic transport[63]. Stagnation encourages the build-up and re-processing of the same air mass and can frequently increase secondary growth. Stronger winds can both ventilate the city and bring in precursor-rich or old aerosol-laden air from the surrounding industrial and agricultural areas. Thus, cleaner or windier weather does not necessarily imply a less powerful effect of nanoparticles. In certain instances, transport can fertilize the urban atmosphere with condensable vapors, as well as those already present, rearranging the growth-scavenging balance in ways that cannot be predicted by local emissions alone.

The most important thing is that meteorology should not be considered a modifier of emissions. It proactively organizes the chemical and microphysical possibilities of nanoparticles. Particle growth is frequently attributed to source-meteorology interaction in Chinese megacities, where both source intensity and meteorological variability are large, rather than to either factor alone[64].

3.5. Regional Transport and Megacity-Cluster Interactions

Chinese megacities are hardly independent atmospheric systems. The majority of them are located within large urban agglomerations, such as the Beijing-Tianjin-Hebei area, the Yangtze River Delta, the Pearl River Delta, and the Chengdu-Chongqing economic circle, where emissions from various cities and industrial belts interact through regional transportation[65]. This has significant consequences for the growth of nanoparticles since transport affects the supply of precursors and the background aerosol burden, which are the two parameters that have the greatest impact on the ability of new or emitted particles to survive and grow.

The contribution of regional transport is in at least three ways. First, it is capable of providing aged aerosol, which enhances condensation sinks and inhibits fresh nanoparticle survival. Second, it can import precursor gases such as sulfur dioxide, nitrogen oxides, ammonia, and organics, thereby boosting the growth of locally formed particles[66]. Third, it can carry already-grown Aitken- or accumulation-mode particles, confounding the boundary between local formation and regional processing[67]. Practically, observed populations of particles in a megacity can be the sum of multiple histories of upwind formation and growth, and not necessarily in situ.

This local view is particularly significant in North China, where large-scale haze has traditionally been associated with synoptic stagnation, industrial belts, and seasonal heating emissions[68]. In these circumstances, the local emission intensity cannot be used to explain the dynamics of urban nanoparticles. The city lies within an extended atmospheric reactor where the plumes age, mix, and recirculate over hundreds of kilometers. The Yangtze River Delta is another more intricate scenario, with industrial discharges, shipping, and heavy urban networks providing good sources of multiphase growth and intercity pollutant exchange[69]. Marine effects and enhanced ventilation can alter these processes in southern megacities along the coast, though regional transportation (via industrial belts and intercity photochemical plumes) still plays a significant role.

One of the key observations is that, in the context of local particle growth, regional transport can either enhance or suppress growth at a certain stage of pollution development[70]. Since transported aerosol loads are large, they can inhibit the survival of new particles through intense scav-

enging. However, in instances where transported precursors are in control rather than transported particle sinks, they can drive local growth. These two effects are hardly captured by mere indicators and can vary throughout the duration of an event. It is one of the reasons why the same meteorological patterns may result in different nanoparticle responses across megacity clusters.

On policy grounds, interactions among regions dispel the belief that local controls in cities are sufficient. A megacity could minimize local emissions and still suffer significant pollution from nanoparticles if the surrounding areas remain active in precursor production. On the other hand, regional cuts could yield greater-than-anticipated returns by reducing the supply of precursors and the background aerosol sinks simultaneously. This is why the growth of nanoparticles should be viewed as a regional governance problem rather than an urban one[71].

3.6. Seasonal and Intercity Variability across Major Chinese Megacity Clusters

The above controlling factors are not similar throughout China. Seasonal differences and intercity variations give rise to discrete nanoparticle regimes indicative of local emissions, meteorology, topography, and policy history. This variability has scientific merit, as it reveals which controlling mechanisms are strong and which are contextual[72].

Cold boundary layers, low temperatures, high levels of combustion-related emissions, and favorable conditions for nitrate partitioning and haze formation are common in winter in northern megacities[73]. These environments can inhibit certain pathways in photochemical processes and amplify multiphase growth and particle persistence. Summer conditions, on the other hand, are generally characterized by higher solar radiation and increased oxidation chemistry, favoring rapid formation and organic growth, but also by increased vertical mixing potential to mitigate near-surface concentrations. It is not merely a seasonal change in pollution intensity, but a change in the prevailing mechanisms of nanoparticle formation.

Eastern megacities of the Yangtze River Delta are usually characterized by high humidity, high-intensity industrial and transport emissions, and complex land-sea interactions[74]. In this case, photochemical organics and aqueous processing can have a significant impact on nanoparticle growth. High temperatures and moisture in southern megacities like Guangzhou and Shenzhen promote strong atmospheric chemistry, but aggressive ventilation and subtropical circulation may shift the ratio between local and regional accumulation. In comparison, basin cities like Chengdu are often characterized by stagnation and a lack of dispersion, which creates prolonged opportunities for secondary processing and particle ageing.

Intercity variability is another indicator of variation in emission-control pathways. Other cities have experienced significant decreases in sulfur and bulk PM2.5, yet still have high traffic-related nitrogen oxides and organic emissions. Still others are more intensely influenced by industrial restructuring or regional agricultural ammonia. These divergent lines imply that the development of nanoparticles cannot be homogenized through a national discourse in Chinese megacities today. Rather, the cities or groups of cities resemble unique blends of antecedent regime, meteorological organization and urban structure.

This variation results in a significant conceptual fact. Chinese megacities cannot be considered as a set of similar phenomena, but rather as a natural experiment of the way in which the aerosol nanoparticle development reacts to various sets of anthropogenic and environmental forcing. Comparative analysis of these cities is not merely descriptive; it is vital for testing mechanisms. By determining where particle growth behaves similarly and where it does not, scientists will be able to better distinguish between universal and city-specific drivers.

3.7. Implications for Understanding and Controlling Nanoparticle Dynamics

Collectively, the data suggest that the growth of aerosol nanoparticles in Chinese megacities is controlled by a highly interconnected system that encompasses the diversity of sources, precursor chemistry, meteorological variations, and interactions at the regional level. Observed variability across events or cities can not be attributed to a single factor. **Table 2** synthesizes the key sources of emissions, the meteorological drivers, and the geographical factors that affect the growth of nanoparticles in Chinese megacities. Traffic and industry are still considered primary anthropogenic drivers, but their effects are conditioned by changing secondary chemistry and the built and meteorological environments in which the

emissions are processed[75]. The region's transport further complicates the situation by moving both precursors and particle sinks between megacity clusters.

One implication is that the dynamics of nanoparticles are highly sensitive to urban atmospheric structural changes[23]. Emission controls that lower the amount of sulfur dioxide might not reduce growth but rather shift it toward organic- and nitrate-based pathways. Decreases in the mass of larger particles can enhance visibility and PM2.5 measurements, but can change the conditions for the survival of new nanoparticles. The redevelopment of urban areas can also alter the microenvironment of street ventilation and exposure without necessarily influencing the regional supply of precursors. These interactions can be used to understand why trends in nanoparticles do not necessarily follow trends in PM2.5 mass.

Table 2. Major sources and controlling factors of aerosol nanoparticle growth in Chinese megacities.

Source or Factor	Key Emissions or Effects	Influence on Nanoparticle Growth	Typical Importance
Traffic	Ultrafine particles, NO_x, VOCs, black carbon	Promotes primary nanoparticle peaks and secondary growth	High in urban cores and roadside environments
Industry	SO_2, NO_x, VOCs, metals, primary particles	Supplies precursors for nucleation, growth, and aging	High in industrialized megacity clusters
Cooking and residential combustion	Organic vapors, soot, semi-volatile compounds	Enhances organic aerosol growth and local exposure	Important in dense residential-commercial districts
Regional transport	Aged aerosols and precursor gases	Can either suppress survival or promote growth	Critical in urban agglomerations
Meteorology	Radiation, humidity, wind, boundary-layer height	Regulates dilution, oxidation, and multiphase reactions	Strong seasonal and regional control

Thus, the Chinese megacities' critical framework ought to transcend source attribution to process attribution[76]. It is not just the source emitting this or that compound, but the interactions among source mixtures, chemical reactions, meteorology, and transport that regulate the pathways between emissions or nucleation and growth, aging, and air-quality relevance. This process-based approach is key in explaining current observations and in formulating future control measures that encompass the particle number and the particle mass in fast-changing urban atmospheres.

4. Observation Methods, Modeling Approaches, and Data Interpretation

4.1. Measurement Challenges in Nanoparticle Research

The growth of aerosol nanoparticles in the urban atmosphere is inherently more challenging to observe than that of bulk PM[2]. This is due not only to the extremely small size of the particles but also to the rate at which their number concentrations, size distributions, and chemical composition vary. These issues are compounded in Chinese megacities, where emissions are extreme and atmospheric conditions vary rapidly not only spatially but also temporally. Responses to traffic bursts, boundary-layer transitions, photochemical activity, and regional plume mixing can also cause changes in nanoparticle populations on a time scale of minutes. Consequently, the availability of sufficient observational systems to measure PM2.5 mass does not necessarily provide the tools needed to understand the underlying dynamics that govern particle growth and survival.

The main problem is that various measurement methods capture different facets of the same phenomenon. The commonly measured variables have different time resolutions, particle chemical compositions, gas-phase precursor concentrations, and meteorological variables with varying time resolutions, detection limits, and sampling artifacts. This introduces a structural imbalance between the processes of interest and available data to characterize them. To take an example, a growth event can be well seen in particle size distributions, yet the condensable vapors may not be directly measured or may be too slow to determine a cause-and-effect relationship. On the other hand, gas-phase chemistry at the highest resolution might be accessible without concomitant information on the development of ultrafine particles. The outcome is that most studies can explain how growth is, but not why it is[77].

This discrepancy is particularly pronounced in Chinese megacities, as the atmosphere frequently operates under mixed regimes. New traffic plumes, industrial emissions,

urban background aerosol and regionally transported pollution may intersect in a single measurement period [78]. Under these conditions, it is methodologically challenging to distinguish the signature of true new particle formation from that of primary emission, or to distinguish local growth from growth that started upwind. The scientific issue is not just a question of how nanoparticles can be measured, but of how measurements can be analyzed in a system where several processes take place and interact nonlinearly.

4.2. Field Measurements of Particle Number Size Distributions

Particle number-size distributions remain the workhorse of nanoparticle observation. Scanning mobility particle sizers, differential mobility particle sizers, and fast mobility particle spectrometers have allowed scientists to follow the dynamics of particle populations at nanometer- to submicron-size scales. These tools are essential because they offer the most direct testimony of formation processes, developmental courses, and changing modal organization. The emergence of a nucleation mode and the subsequent growth to larger sizes are among the most obvious indicators of active nanoparticle growth in urban studies [10].

The usefulness of size-distribution measurements, however, is highly sensitive to the size range that can be detected and to the time resolution [79]. In megacities of China, cluster formation and initial growth stages can dictate the survival of particles in strong sinks of coagulation, and failure to resolve the smallest size bins can result in incomplete or misleading interpretations. Such instruments, which initiate detection at a few nanometers, might detect subsequent growth but fail to distinguish between molecular clusters and stable nanoparticles. Concurrently, a lack of temporal resolution may blur the rapid evolution of events and the connection between emissions, photochemistry and particle growth. This is especially objectionable around traffic corridors or in high-density urban areas where source influence may vary on shorter timescales than traditional scan cycles.

Another complication is that size-distribution measurements alone do not distinguish primary emissions from secondary formation [80]. The burst of ultrafine particles around a roadway can be similar to the initial phase of a new formation event of a particle, but the processes are completely different. This is a real threat in Chinese megacities, where roadside emissions and photochemical smog often coexist. This has contributed to the increasing focus on combining particle number size distributions with co-located gas-phase tracers, black carbon measurements, and meteorological measurements. This kind of integration enables researchers to deduce whether a measured population of nanoparticles is a result of local combustion emissions, atmospheric nucleation, regional transport, or a combination of both.

Nevertheless, long-term size-distribution measurements can be considered among the most useful for understanding urban nanoparticle regimes [23]. They offer the time continuity to define the seasonal trends, changes due to policy influence and the disparity within the megacity clusters. But they are most effective when they are not considered as self-contained data products but as part of a larger diagnostic process.

4.3. Chemical Characterization of Particles and Precursor Vapors

The size information alone cannot provide a mechanism, since the mechanism arises from the condensation and transformation of chemical species. Observational uncertainty is most acute where chemical characterization is needed, however. For larger submicron aerosols, aerosol mass spectrometers and filter-based analyses have provided substantial information on sulfate, nitrate, ammonium, organics, and trace species. In the case of nanoparticles, however, chemical analysis is more challenging due to their low mass, rapid variability, and difficulty in sampling without significant artifacts [81].

The latest developments in online aerosol mass spectrometry, thermal desorption techniques, and particle-into-liquid sampling have enhanced the capacity to characterize sub-100 nm particle composition, particularly in the transition from the nucleation mode to the Aitken mode [82]. These instruments have shown that the expansions of Chinese megacities tend to entail a complicated blend of sulfur-containing substances, oxidized organics, nitrate-related species, and secondary inorganic material. However, it is hard to tell, since measured composition usually reflects an already evolved state, not the chemical forces of the earliest growth stages. That is, the compounds in the particles at 20 or 50 nm need not be the same as those which regulate survival at 2 or 5 nm.

Measurements of precursors in the gas phase are also

important and difficult. New capabilities for detecting sulfuric acid, highly oxygenated organic molecules, amines, and other low-volatility vapors associated with nanoparticle growth have been achieved using instruments such as chemical ionization mass spectrometers[18]. These observations have assisted in the transition to multi-precursor structures of organic oxidation products and in a focus on nitrate chemistry in Chinese megacities, rather than overly simplistic sulfuric-acid-based explanations. Nevertheless, they are costly, technologically challenging and have not yet been commonly implemented in coordinated long-term urban monitoring networks. Consequently, proxy indicators or inferred precursor contributions are still used in many studies, instead of direct chemical evidence.

A critical interpretive problem is that precursor measurements tend to focus on instrumentally accessible species rather than the mechanistically most relevant ones. This has the potential to skew science. An easily measurable compound might seem central because it is easy to see, and an equally important but immeasurably badly measured category of vapors remains underrepresented. This is of particular concern for semi-volatile and intermediate-volatility organics, which may be important components of growth but are difficult to fully understand in real urban environments. Present chemical characterization is therefore very powerful, but at the same time still represents only a section of the spectrum of volatility that rules the development of nanoparticles[83].

4.4. Multi-Platform Observations and Integrated Monitoring Strategies

Single-site measurements, though useful, can hardly be used to clarify the entire dynamics of nanoparticle growth in megacities. Chinese urban air pollution is defined by the power of spatial gradients, such as near-road hotspots, industrial plumes, residential-commercial mixtures, urban-background areas, and peri-urban interfaces where regional transport takes into consideration. This is why integrated monitoring strategies involving a combination of several sites as well as mobile observations, vertical profiling, and remote sensing are gaining more and more importance[84].

Urban super sites that have high-resolution particle, gas, and meteorological instrumentation provide in-depth process-level information, yet they run the risk of overrepresenting the local situation of a particular neighbourhood[85]. A roadside site can be used to bring out traffic bursts of nanoparticles, whereas an urban-background site can be used to bring out regional secondary growth. The city-wide system can not be represented by either of them individually. The multi-site networks are thus important in identifying the local emission signatures as compared to those of a larger urban or regional behavior. Comparative studies between the urban areas in the center of the megacities, their peripheral locations and downwind receptors have proven particularly effective in following how nanoparticles are generated, develop and change over time as air masses pass through the metropolitan setting.

Mobile measurements and vertical observations are a new dimension. The gradients of number concentration near roads, industrial sources, and urban canyons can be mapped using vehicle-based campaigns, which indicate the microenvironmental structures not seen by fixed stations[86]. The contribution of mixing, entrainment, and development of the boundary layer in the control of nanoparticle survival can be revealed by vertical measurements, e.g., by tower, drone, or aircraft[87]. This is particularly applicable in urban areas whereby the redistribution of particles and precursors up the height is enhanced by the rapid growth of the morning boundary layer. Surface observations cannot distinguish between true chemical change and the simple effects of dilution or mixing without vertical information.

The direct contribution that remote sensing can make to nanoparticles is a smaller one since the satellites do not directly resolve the number of ultrafine particles. However, satellite data can be utilized in contextualizing aerosol optical depth, precursor gases, land-use structure and regional transport patterns[88]. They are actually strong in assisting interpretation and not substituting for in situ measurement. Hierarchy will probably be the most fruitful strategy in future urban monitoring systems: detailed in situ measurements to understand processes, multi-site networks to be spatially representative, and more encompassing remote-sensing or models to represent the regional context.

4.5. Derivation and Interpretation of Growth Parameters

One significant objective of nanoparticle observation is to translate raw measurements into process measurements.

Some of the most popular ones include particle growth rate, formation rate, condensation sink, coagulation sink and survival probability[38]. The appeal of these metrics lies in the fact that they present such a concise description of the dynamics of particles and can be compared across sites and studies. They are, however, not directly observable, but derived quantities, based on assumptions about mode structure, time continuity, and process separation. Their usefulness is thus determined by their interpretation level of criticality.

The rate of growth can be estimated by the change in the time center of a particle mode to larger diameters[89]. This method may be very informative, although it presupposes that the observed mode is the same population of particles through time. That assumption might not always be true in Chinese megacity atmospheres, where the various populations of sources can overlap and local emissions can inject fresh particles at any moment. The apparent increase can be partially due to the mixing of various populations of particles, and not necessarily to the condensational expansion of a particular population. Equally, growth rates calculated over large size ranges could be misleading in that the controlling process may be different between the initial nanometer-scale growth and subsequent expansion into the Aitken mode.

The rate of formation is also subject to similar ambiguity. It is typically determined based on the rate of appearance of particles at a cut-off size, with a correction for losses and growth beyond that size bin[90]. However, this threshold-based technique can be very sensitive to instrument range and assumptions of loss. Small inaccuracies in the loss estimation can yield huge uncertainties in the formation rates inferred in the polluted Chinese cities with high condensation sinks. This means that caution should be exercised when comparing the intensity of events in cities or seasons unless the measurement and analysis procedures are synchronized.

Another commonly used measure is the condensation sink, which is designed to measure how rapidly condensable vapors are lost to already existing aerosols[91]. It is highly beneficial in contaminated surroundings since it connects background aerosol load and the survival issue of new particles. But condensation sink is not a mere passive term; it dynamically interacts with the same processes that researchers are interested in understanding. The suppressive effects of high sink conditions on survival can be offset by high precursor abundance and robust multiphase chemistry that enable rapid growth. Therefore, the condensation sink is not to be taken as a straightforward obstacle. Its impact in Chinese megacities can be highly dependent on the co-evolution of emissions, humidity, and oxidation capacity.

These problems indicate a more general point that process metrics are necessary, yet they should not lose touch with their assumptions. They should be regarded as a diagnostic guess at most and not a physical fact. They have more interpretive value when many metrics are considered simultaneously and when the uncertainties are made public.

4.6. Box Models and Process-Oriented Frameworks

Observational data are often combined with process models in order to pass the stage of description to the explanation stage. Box models are some of the most widely applied tools to interpret the growth of nanoparticles, in that local chemistry and microphysics are treated in detail without the computational complexity of complete three-dimensional transport models[92]. Box models are particularly used in urban studies to test hypotheses related to contributions of precursors, volatility distributions, and sensitivity to the level of oxidants or meteorological conditions.

Their primary virtue is the mechanistic clarity. Box models can be used to determine whether the observed growth rates are proceeding as expected based on measured sulfuric acid concentrations, oxidized organic vapors, oxidized nitrate formation, or mixed condensation pathways[93]. They come in especially handy when used in conjunction with intensive field campaigns in Chinese megacities, where researchers aim to ascribe particular episodes of growth to particular chemical drivers. With sensitivity analyses, such models can also provide insight into how variations in the emissions of the precursors could change the growth under otherwise comparable conditions.

Meanwhile, box models are not without limitations. They tend to use simplified models of air mass history, dilution and mixing, which are all very significant in the actual megacity[94]. A box model can recreate the growth that has been observed in a measurement location but it does not capture the fact that particles were created upwind, entrained aloft, or by changing urban plumes. Furthermore, the chemistry of urban organics is too complicated to the extent that numerous box models typically pool compounds in

simplified classes of volatility or yield structures. These approximations can be helpful, yet they can conceal important nonlinearities of dependence on nitrogen oxides or reactions with heterogeneities or with multiphase aging.

What is crucial is that box models are only most informative when applied as hypothesis-testing instruments and not as full descriptions of the urban atmosphere [95]. Their conclusions are to be assessed on independent observational constraints and, wherever feasible, incorporated into scales of modeling.

4.7. Chemical Transport Models and Urban-Scale Simulations

Chemical transport models in three dimensions offer a more comprehensive view of how nanoparticle processes are related to city-wide and regional air quality [96]. These models are also necessary when the scientific question is not limited to a single location of observation, but when transport at a regional level, intercity interactions, policy situations, and long-term trends are crucial. They have special significance in the Chinese megacities, where nanoparticles tend to grow locally within larger megacity-cluster pollution regimes.

The chemical transport models have the ability to simulate the emissions, gas-phase chemistry, aerosol microphysics, deposition and meteorological fields over extensive areas [97]. This renders them potent instruments to investigate the impact of precursor decreases in a single area on the development and expansion of particles in another, or the impact of an alteration of the conditions at the boundary layers on the overall exposure in the city. They are also becoming more and more applied to determine how changes in sulfur, nitrogen and organic emissions can alter the prevailing growth pathways of nanoparticles in contemporary Chinese atmospheres.

However, it is still challenging to model nanoparticle dynamics in such models. The initial processes of cluster formation and development are extremely sensitive to local-scale chemistry and size-resolved microphysics, which are difficult to solve at regional scales. The parameterizations are thus inevitable but can cause a lot of uncertainty. Numerous models continue to describe nucleation by simplified sulfuric-acid-based models or by bulk organic aerosol treatments which are unable to completely describe size-dependent growth. Simplifications can both yield the right PM2.5 mass by chance and fail to capture dynamics of particle numbers in the densely populated urban atmosphere [98].

The finer spatial representation and ability to model near-source dispersion and built-environment effects are found in urban-scale simulations, such as computational fluid dynamics and street-canyon models. These methods can be useful in the study of exposure hotspots and urban form effects on the behavior of nanoparticles. They tend, however, to work within narrow domains and might not take into account the entire regional chemical environment that affects growth. The problem is, then, a scale coupling problem. Chemical transport models represent regional interactions, but fine details of the street-level process are frequently poorly resolved, and urban microenvironment models represent local structure, but do not necessarily capture large-scale precursor and transport processes. Further development will rely on more powerful unification of these scales [99,100].

4.8. Data-Driven Methods and Machine Learning Applications

With the increasing scope and multidimensionality of observations in Chinese megacities, data-driven approaches are coming to be used to determine patterns, categorize events, and deduce controlling relationships. Large datasets incorporating particle size distributions, gas-phase precursors, meteorology, traffic indicators, and remote-sensing variables can be useful to machine learning approaches [101]. They are specifically appealing in terms of predicting the occurrence of events, discovering nonlinear dependencies, and bridging gaps in which direct mechanistic modeling is either computationally or chemically demanding.

The value of these methods is evident particularly in complex urban systems where the traditional linear analyses could not realize interacting effects. Indicatively, machine learning models have the ability to disclose humidity-solar radiation-nitrogen oxides-background aerosol loading combinations that are uniformly observable in advance of robust nanoparticle growth events [102]. They are also capable of helping to categorize observed bursts of particles as probable as traffic-related or secondary. They can assist in the detection of intercity similarities and contrasts, which could not be identified by other means alone in megacity networks, except by manual inspection.

Nonetheless, data-driven approaches are also associated with high risks. When there are highly covarying variables in the atmosphere, correlation can be easily confused with mechanism. The growth can be predicted by a model without knowing the real chemical drivers. This can be especially problematic where it is part of policy making, where interpretation is as important as prediction. Additionally, machine learning processes rely largely on the form and representativeness of the training data. In case the observations are biased with respect to specific seasons, sites, or pollution regimes, the models that are derived can be poorly generalized [103].

This is why information-based methods cannot be regarded as alternatives to physical knowledge. Their most useful use is as complementary instruments: they help find patterns, formulate hypotheses, and assist hybrid frameworks where mechanistic knowledge limits statistical inference. Such hybridization can be particularly useful in nanoparticle studies, where nonlinear processes are being studied that are only partially observable.

4.9. Source Apportionment and the Problem of Attribution

Attribution is one of the most lingering interpretive issues in nanoparticle studies. Policymakers would like to understand which sources are the most important, but sources do not influence nanoparticle growth in a one-to-one manner. The source of traffic, such as it, can be important due to its direct emissions, the production of nitrogen oxides and aromatics that will contribute to the subsequent expansion, or the fact that it changes the oxidative environment in the city in general. Industrial emissions can be a source of sulfur dioxide, organics, and metals at the same time, and regional agriculture may be a source of ammonia, which alters the particle chemistry in the city, but is not even present there [104]. The question is not then merely of which source the particles were emitted, but of which sources the observed growth pathway was facilitated.

Bulk composition-based source apportionment and traditional receptor models tend not to be effective in nanoparticles as compared to larger particles due to the small mass of the tiniest particles and their ability to chemically develop prior to sampling [105]. Attribution can be unstable as source signatures can be quickly transformed or diluted. Source apportionment at the size scale would help to mitigate the situation; however, only when adequately detailed data on composition and realistic process assumptions. In Chinese megacities, where the primary and secondary influences are fully mixed, only statistical source apportionment can underestimate cross-source coupling.

This implies that process attribution can be more effective than traditional source attribution for nanoparticles [106]. Rather than attributing a fixed proportion of particle mass or number to a subset, researchers might need to distinguish among pathways such as sulfur-driven early growth, organic-dominated daytime growth, nitrate-enhanced humid growth, or traffic-induced roadside nucleation-like bursts. Such pathways can subsequently be traced back to emission sectors and policy levers in a more realistic way. This method is analytically more challenging, yet more indicative of the coupled chemistry of Chinese urban atmospheres.

4.10. Uncertainty, Comparability, and Future Methodological Needs

Although significant progress has been made, a key obstacle to synthesizing across studies is the lack of methodological comparability. Estimates of growth and formation rates under similar atmospheric conditions can vary significantly depending on the instruments, size cutoffs, averaging periods, event definitions, and analytical assumptions. This issue is of particular concern in review work, since the apparent differences between the Chinese megacities might be partly due to methodological inconsistencies rather than to actual atmospheric contrasts [107].

At each step, uncertainty is high: sampling losses at the inlets of ultrafine particles, detection at the smallest sizes, incomplete coverage of the chemical, simplified mechanisms in the model, and uncertainty in the separation of local and transport effects [108]. But these uncertainties are not just technicalities; they inform the scientific inferences that may be made. One city may appear to have less robust nanoparticle growth than another because the earliest steps were not quantified, or precursor measurements were insufficient to identify a dominant pathway.

Integration and standardization should thus be put on the center stage of future methodological developments. Multi-city efforts with coordinated size-distribution measurements, on-the-fly precursor measurements, high-resolution meteorology, and common analytical frameworks would

significantly enhance the comparability of China's megacities[16]. There is also a need for greater integration between long-term routine monitoring and short-term intensive campaigns, as the former offers representativeness and the latter mechanistic detail. No less significant is the more robust integration of observations and models with explicit uncertainty analysis, rather than post hoc curve fitting.

The development of measurement and modeling in this domain is, more broadly speaking, a shift in the scientific focus. It is no longer in question that nanoparticle growth has increased in Chinese megacities; this has been well established. The more challenging question is how to observe and interpret it in a manner that is precise enough, chemically relevant, and policy-relevant. To realize this objective, it is necessary to transcend single measurements or single models to integrate inferences across scales, techniques, and cities. **Table 3** compares the major observational and modeling methods employed to study nanoparticle growth, along with their strengths and limitations. An integrated observation–modeling framework for reducing uncertainty and improving process attribution is proposed in **Figure 2**. The figure provides an organized structure that connects the particle number-size distributions, chemical composition, precursor measurements, supersite observations, mobile monitoring, box models, chemical transport models, urban-scale simulations, and machine-learning tools[109].

Table 3. Observation and modeling approaches for studying aerosol nanoparticle growth.

Approach	Main Application	Strengths	Limitations
Mobility particle sizing	Measures particle number size distributions	Directly identifies growth events	Limited chemical information
Aerosol mass spectrometry	Determines particle composition	Reveals inorganic and organic aerosol chemistry	Difficult for the smallest nanoparticles
Chemical ionization mass spectrometry	Measures precursor vapors	Links vapors to growth mechanisms	Expensive and technically demanding
Multi-site monitoring	Tracks spatial variability	Distinguishes local and regional effects	Requires harmonized instruments
Box modeling	Tests chemical and microphysical mechanisms	Useful for process diagnosis	Simplified transport representation
Chemical transport modeling	Simulates urban-regional pollution	Supports policy and scenario analysis	Uncertain nanoparticle parameterizations
Machine learning	Classifies events and detects patterns	Handles nonlinear datasets	May lack mechanistic causality

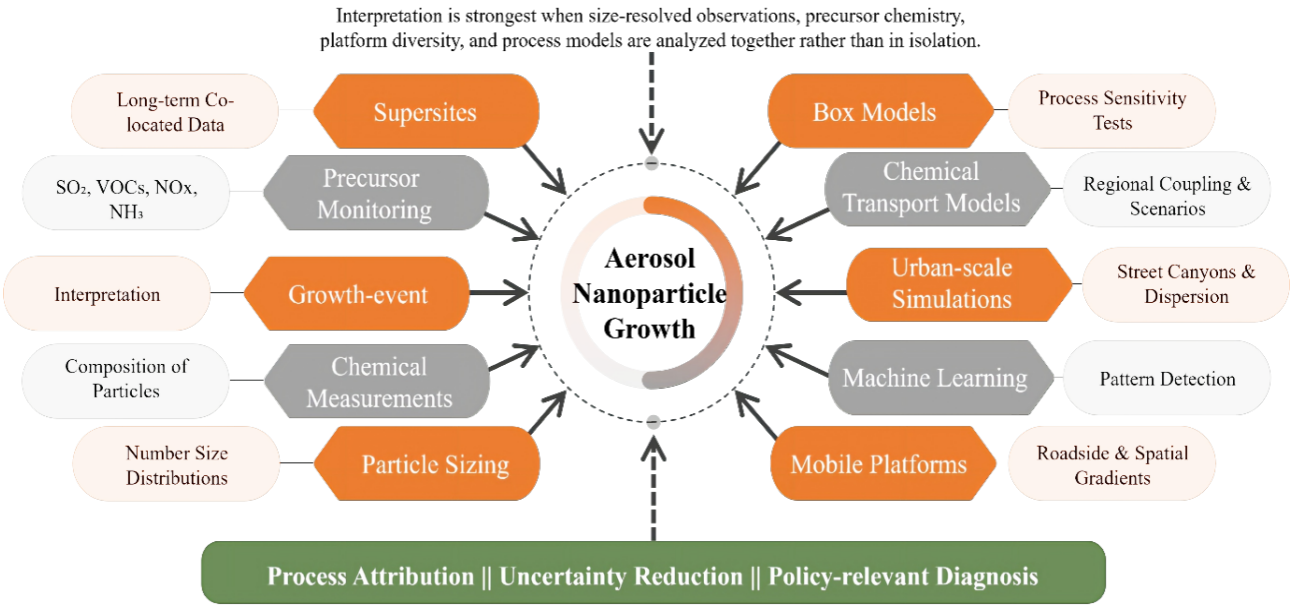

Figure 2. Integrated observational and modeling framework for nanoparticle growth studies in Chinese megacities.

5. Impacts on Urban Air Quality, Human Health, and Pollution Control

5.1. Nanoparticle Growth as a Bridge between Ultrafine Pollution and PM2.5 Evolution

Aerosol nanoparticles and their effects on urban air quality cannot be explained only by their initial number concentration or the frequency of their formation [23]. Their greater importance in the environment stems from their ability to reach larger size groups that directly impact fine particulate pollution, atmospheric visibility deterioration, and haze formation in the region. In this respect, the growth of nanoparticles is the phenomenon that links the short-lived events of molecular or ultrafine particles to the more enduring impacts on the particulate burdens commonly employed in air quality analysis. This mediating position is particularly critical for Chinese megacities, where extreme pollution events are typically driven by the interplay of high precursor emission levels, rapid secondary formation, and effective particle growth under stagnant, humid conditions.

At the formation stage, nanoparticles contribute a negligible mass to particulate matter, but they may have a disproportionate impact on the subsequent development of PM2.5 should growth occur. When particles enter the most susceptible loss regime and reach the Aitken and accumulation modes, they begin to play a more significant role in aerosol surface area, mass concentration, and light scattering. Such a shift is not only a gradual increase or decrease in size, but rather a qualitative change in atmospheric relevance. Previously of interest only as particles, primarily due to their number concentration and inhalation toxicity, they are of growing significance to haze chemistry, cloud activation, and regulatory PM metrics. Thus, nanoparticle growth is an important field that helps us understand the urban atmospheric transformation of gaseous pollution into mass-based particulate pollution [2].

This change is particularly important in Chinese megacities due to the high precursor loadings, which enable numerous pollution episodes to transition to mass-dominated haze events much faster than in chemically active but low-mass nanoparticle regimes. Many conventional air quality models tend to treat ultrafine particle pollution and PM2.5 as two partially distinct issues, whereby the former is linked to number and exposure, and the latter to mass and visibility. In practice, though, these are often associated with the same air path. The growth of nanoparticles is the process by which that pathway is achieved. It may seem that a city is shifting toward a particle-number problem and a PM2.5 problem. Still, the process behind it is a continuous, chemically mediated expansion of the particle population [110].

Its critical implication is that the mass concentrations of PM2.5 in the air do not provide the complete picture of the dynamics of pollution evolution. The microphysical history of two urban events with similar PM2.5 peaks can differ dramatically in whether growth was by mass accumulation via direct emissions, condensation onto existing particles or rapid growth of newly formed nanoparticles. These differences are important because they affect chemical composition, toxicity, optical properties, and policy responsiveness. The growth of nanoparticles, therefore, can no longer be regarded as a marginal process that the usual mass control cannot detect, but rather as one of the upstream mechanisms that contribute to either the absence or the increase of urban PM2.5 episodes [111].

5.2. Contribution to Haze Formation, Visibility Degradation, and Atmospheric Radiation

Among the most apparent effects of nanoparticle growth in Chinese megacities is their contribution to haze formation [112]. Haze can be defined as high PM2.5 mass and low visibility, but its physical mechanism depends on the aerosol size distribution and chemical composition. The more nanoparticles enter the accumulation mode, the more effective they become at scattering visible light, particularly those composed of hygroscopic inorganic and oxidized organic materials, which absorb water in humid environments. The growth thus changes not only the quantity of the particulate matter, but also its efficiency at impairing atmospheric transparency.

This difference is significant because total mass is not the sole determinant of visibility impairment. The aerosol optical effects depend on the size range over which the particles enlarge, the refractive characteristics of the materials they are composed of, and the degree of hygroscopic swelling under ambient humidity. A population of particles that expands by tens of nanometers to the lowest accumulation mode can become much more optically active than it was initially at creation, before the dramatic increase in total mass. This op-

tical amplification is particularly high in Chinese megacities, where haze events tend to happen under humid relative conditions. The processes of growth and water uptake reinforce each other, enabling particles to scatter additional light and make them less visible[113].

The radiation balance in the urban environment is also influenced by nanoparticle growth, which has impacts beyond visual haze. The population of particles moving to optically active sizes will affect the absorption and scattering of solar radiation. It may alter the formation of the boundary layers, surface temperatures and photochemical activity. This brings in a feedback loop. Improved particle development may reduce incoming solar radiation at the surface, thereby undermining turbulent mixing and trapping pollutants in a thinner layer. That confinement can then maintain that high concentration of gases and particles required for further secondary formation. This is to say that nanoparticle development can be involved in self-reinforcing changes in haze development, not just by contributing to particulate matter burdens but also by influencing the meteorological conditions under which those burdens grow[114].

The feedback mechanism is particularly applicable in Chinese megacities because there is a tendency for simultaneous variations in microphysics, chemistry, and boundary-layer processes related to pollution episodes. The change between clear and hazy conditions is not the cumulative deposition of particles but rather a coupled system response. Growth of nanoparticles contributes to the same response, increasing the heterogeneous reaction surface area of aerosols, facilitating hygroscopic growth, and enhancing the optical efficiency of the particle population. Such variations help explain why the occurrence of certain urban pollution events increases rapidly, even when precursor emission levels do not vary significantly over a number of days[115].

An important point to note is that the climatic and radiative relevance of nanoparticles is not primarily determined by their initial existence but by their growth pathway. New nanoparticles are typically too tiny to be the dominant players in the extinction and cloud condensation events in the visible spectrum. Still, once large enough and aged, they may be the central actors in urban radiation perturbation. The effects of the nanoparticles on haze and radiative forcing are thus not direct; they are a product of growth-induced changes[116].

5.3. Effects on Atmospheric Oxidation Capacity and Heterogeneous Chemistry

The formation of nanoparticles affects city air quality by altering particle size and mass and changing the chemical balance of the air[117]. The overall aerosol surface area generally increases with particle size, offering more heterogeneous uptake and multiphase reaction interfaces. These reactions can modify the concentrations and cycling of oxidants, precursor gases, and reactive intermediates. Such surface-mediated pathways can be important constituents of episode formation in highly polluted urban atmospheres.

An increase in the surface area of the aerosol population increases the ability to absorb and transform gases such as nitric acid, ammonia, oxidation products of sulfur dioxide, and semi-volatile organics[118]. Aerosol liquid water in wet weather further increases the reactive medium and promotes aqueous-phase chemistry. As a result, the growth of nanoparticles can facilitate the transition from a gas-phase-based atmosphere to a more heterogeneous, multiphase-based one. This change can frequently be observed in the maturation of haze events in Chinese megacities, when the later phases of pollution can be more chemically efficient, even with weakened sunlight or turbulent mixing.

This has significant implications for atmospheric oxidation capacity. Oxidants can be consumed and redistributed by aerosols. On the one hand, the expansion of the particle phase has the potential to eliminate reactive gases in the atmosphere through partitioning and uptake. Conversely, reactions in the particle phase can produce secondary species that continue to form aerosols. The overall impact is usually nonlinear and episode-specific. In other situations, increasing aerosol loading inhibits photolysis and reduces radical generation at the surface[119]. In other instances, multiphase reactions counteract this by providing additional conversion routes for particulate precursors. These interactions complicate straightforward accounts in which particle pollution is considered an active effect of gaseous chemistry. The chemistry of nanoparticles can be actively reconfigured by their growth.

This feedback is especially important in Chinese megacities, as elevated precursor levels and sensitivity to humidity are conducive to aerosol-driven increases in the formation of secondary inorganic and organic aerosols[120]. When particles become large enough to provide significant reactive

surface area, the atmosphere can be more efficient at producing particulate material. This is one reason the line between primary and secondary control, and between chemistry control, is not as distinct. Nanoparticle growth not only turns particulate pollution into a product of atmospheric processing but also regulates it by influencing the surface-mediated reactivity of the aerosol system.

An important implication for the science of air quality is that the evolution of particle sizes must be more explicitly incorporated into the chemical analysis[121]. When aerosol growth accessibility expands surface area and liquid water to the extent that it alters the pathways of oxidation, the microphysical and chemical processes cannot be investigated separately. In that respect, the nano-environmental impact of nanoparticle growth is partly that it converts the atmosphere into a more efficient nanoparticle-growth reactor.

5.4. Human Exposure and Health Implications of Growing Nanoparticles

Nanoparticles, due to their very small size, high concentration, and profound penetration into the respiratory system, have frequently been viewed as having health implications[122]. These properties are essential, yet the dynamics of growth make the picture more problematic. Nanoparticles do not remain as exposure agents. Their size, composition, hygroscopicity, and toxicity change over time, in the same way that urban populations come into contact with them. This implies that not only the number of nanoparticles present but also the changes they undergo before inhalation can lead to a health risk.

Newly emitted or new nanoparticles can deposit effectively within the alveolar region due to their small size and high diffusivity[123]. They frequently harbor reactive surface chemistry, such as organics from combustion, transition-metal or reduced compounds. As they develop, however, their deposition efficiency varies across different locations in the respiratory tract, and their chemical complexity tends to increase with condensation and age. Increased growth can raise the proportion of oxidized organics, acidic constituents or secondary inorganic species related to inflammatory processes and oxidative stress. Therefore, increased particle numbers resulting from nanoparticle growth need not be merely diluted or less dangerous forms of the initial population. Growth may, in other instances, enhance toxicological relevance, for example by increasing particle persistence, altering surface reactivity, or enabling the transport of more chemically complex materials[124].

This is highly critical in Chinese megacities, where exposure occurs in highly heterogeneous microenvironments. Near-road populations could be exposed to newly emitted nanoparticles with high concentrations of combustion products. Still, urban-background populations could experience increased exposure to older particles that have grown significantly through secondary processes. The problem of indoor infiltration further complicates this trend, as the penetration and retention of particles of various sizes and types in indoor environments vary. Consequently, nanoparticle pollution cannot be well represented in the public health burden by a single measurement type or a single exposure measure. It depends on the number concentration, size distribution, chemical aging, and the time co-occurrence with other pollutants[125].

Another problem is that regulatory frameworks have mainly focused on the mass of PM2.5 and PM10, which fail to capture the number burden and changing surface properties of nanoparticles[15]. A city can achieve high levels of mass-based air quality improvement, yet leave its residents at risk of episodic or chronic exposure to ultrafine particles. Indeed, there are cases of emission-control conditions that can reduce the mass of larger particles more than the number of nanoparticles, or alter the relationship between direct emissions and secondary development in ways that alter exposure patterns without apparent mass-concentration variations. This disassociation helps clarify that health issues related to ultrafine particles remain substantial even in areas where bulk PM indicators have improved.

Another key conceptual consideration is the relationship between nanoparticle growth and health. Toxicity is not emission-fixed[126]. Part of its production occurs in the atmosphere through aging and growth. The atmosphere is a chemical processing unit that alters the biological significance of the inhaled particles. This view is critical in the case of Chinese megacities, where emissions, humidity levels, and oxidation conditions usually support quick change. It implies that the protection of the health of the population should not focus on the source emissions, but also on the atmospheric conditions that transform the said emissions into more stable and possibly harmful populations of particles.

5.5. Implications for Air Quality Standards and Monitoring Strategies

The pivotal role of nanoparticle development in urban air quality reveals a gap in the framework for traditional air pollution observation and control [127]. The current standards in most areas, including those used in air management frameworks in Chinese cities, rely primarily on mass-based measures of particulate matter such as PM2.5 and PM10. These measures are essential for protecting human health and enforcing policy, but fail to address particle number concentration, initial growth, or the microphysical processes that determine whether newly formed nanoparticles enter the regulated fine-particle burden. Consequently, a significant component of the aerosol system remains virtually undetectable by regular monitoring systems.

This restriction has policy and scientific implications. Scientifically, mass-based monitoring can measure growth outcomes once particles have acquired sufficient mass to influence PM2.5. Still, it cannot record the dynamics that precede mass accumulation and determine whether it will occur. Policy-wise, dependence on PM2.5 might provide an incomplete or delayed view of aerosol development in urban areas. The particle-growth processes that generated the event might already be in full swing by the time PM2.5 gets big. On the other hand, when emission controls lead to decreases in mass concentrations and to high or changing numbers of nanoparticles, or when the growth direction changes in response to chemical conditions, regulation can overestimate the extent of improvement [15].

This does not mean that mass standards are not sufficient and ought to be pushed out. Instead, it implies that they must be supplemented with more process-sensitive observations [128]. Particle number size distributions, ultrafine particle counts, condensation growth indicators, and the precursor gases of interest would be routinely measured to provide a more comprehensive foundation for interpreting changes in urban aerosol. These additions would be particularly useful in Chinese megacities, since policy has already pushed many cities into a transitional phase in which bulk PM2.5 has declined. Still, secondary processes remain very strong. One might no longer be able to rely on monitoring systems intended to track historically mass-dominated pollution to track the chemically changing urban atmospheres.

Another related problem is network design. Regulatory monitors are frequently positioned to evaluate overall compliance and population exposure, rather than to measure particle growth mechanisms [129]. However, nanoparticle dynamics are much more sensitive to the microenvironment, urban morphology and regional coupling. Compliance-oriented monitoring would be better integrated with process-oriented supersites and mobile measurements, and would enhance interpretation and policy relevance. It is not a technical expansion but an expansion of conception: the city's air quality must be viewed as a dynamic system in which particle counts, growth, and chemistry are important, in addition to mass concentration.

5.6. Effectiveness and Limits of Current Control Strategies

The last ten years have demonstrated that intensive air quality management can significantly reduce PM2.5 levels in China's megacities. These gains indicate an effective effort to reduce sulfur dioxide, industrial releases, coal burning, and primary particle emissions. Nonetheless, these achievements pose new challenges for nanoparticle growth dynamics. The processes that govern particle growth can also change with changes in the pollutant mixture. A decrease in one of the main precursors does not always result in the loss of aerosol growth; it may redistribute chemical drivers [61].

To illustrate, a reduction in sulfur emissions can reduce both nucleation and early growth driven by sulfuric acid, while also enhancing the relative significance of nitrate and organic condensation routes [130]. Under certain conditions, decreases in the mass of larger particles can reduce condensation sinks and, therefore, increase the probability of survival of newly formed nanoparticles. Alterations in vehicle fleets can reduce soot or sulfur emissions and leave nitrogen oxides, volatile organics, and traffic-induced ultrafine particle bursts as chronic problems. These dynamics imply that the policy's success in one dimension can give rise to a new atmospheric regime in which previously secondary processes become more dominant.

This does not reduce the value of the controls in place. Instead, it points to the fact that policy is taking a more complicated phase. The target of early pollution control in most Chinese cities was right, as it concentrated on the most noticeable and mass-intensive sources. The second step involves a smaller step of precursor mixtures, atmospheric process-

ing, and concurrent control of particle number and mass. Strategies that are industry-specific and not process-coupled can deliver decreasing returns. For example, although reducing emissions from one source might not significantly reduce nanoparticle-related pollution, other sectors might still provide the organics, nitrogen compounds or ammonia that would enable growth [2].

An important lesson learned is that the control of pollution should be progressively considered in terms of atmospheric response rather than necessarily in terms of changes to the emission inventory. The thing is, the reorganization of the urban atmosphere occurs after the controls are applied. Should chemical regimes become more sensitive to nitrate, or more actively involve organic processes, or be more active in the humid phase, future benefits will lie in predicting such changes rather than responding to them once they are reflected in monitoring data. In this regard, the dynamics of nanoparticle growth can serve as a diagnostic prism through which the impact of control policies on the conditions for the development of secondary aerosol or on the prevailing direction of its growth can be evaluated [116].

5.7. Toward Coordinated Multipollutant and Multiscale Management

The discussion above indicates that comprehensive management of the air-quality effects of nanoparticles in Chinese megacities requires a multi-pollutant approach. Since growth is determined by interactions among precursor gases, aerosol sinks, humidity, oxidation conditions, and transport, single-pollutant models may be inadequate. Sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds must be addressed not only as individual emissions but also as part of an interconnected atmospheric system [131]. Their joint control is especially significant since the effect of the same reduction may vary depending on the chemical regime in place.

This also means that the management must be cross-scaled. Local traffic and urban design interventions might be needed to address roadside ultrafine particle exposure, and regional haze associated with nanoparticle growth might necessitate precursor reduction at the megacity-cluster level [132]. Likewise, city health protection requires both a reduction in outdoor concentrations and a better understanding of infiltration and the microenvironment. A city-focused approach that neglects regional ammonia or industrial transportation will be incomplete, and so will a regional approach that neglects near-road number concentrations.

Practically, future management would shift towards integrated measures and process-based assessment. This does not imply that new regulatory standards for ultrafine particles will be adopted immediately, but such deliberations may become more important. It does imply that planning, monitoring, and assessment must be more explicit about the pathways through which particles can be formed, grow, and age. The control strategy must be evaluated not only by the extent to which it decreases PM2.5 mass, but also by whether it undermines the atmospheric processes that maintain high particle concentrations, rapid secondary growth, and chemically persistent haze [133].

In the case of Chinese megacities, such coordination is especially urgent, as the urban environment is already changing. Most apparent mass-dominated pollution has been reduced in most places, but the residual issues are more nonlinear and chemically complex. The dynamics of nanoparticle growth indicate why this is the case. They demonstrate that the quality of air in the city is not determined by the quantity of pollution generated, but by the atmospheric pathways through which this pollution is converted [134]. The major air quality, health, monitoring, and policy implications of nanoparticle growth are summarized in **Table 4**.

Table 4. Air quality, health, and policy implications of aerosol nanoparticle growth.

Impact Area	Role of Nanoparticle Growth	Key Implication
PM2.5 formation	Converts ultrafine particles into larger particulate mass	Growth dynamics should be considered in PM2.5 control
Haze and visibility	Enhances light scattering after particles enter optically active sizes	Size-resolved monitoring is needed
Atmospheric chemistry	Increases aerosol surface area and multiphase reaction potential	Growth can accelerate secondary pollution formation
Human health	Alters deposition, persistence, and chemical toxicity	Particle number and composition matter beyond mass
Monitoring	PM2.5 and PM10 do not capture early growth dynamics	Ultrafine particle and precursor measurements should be added
Policy control	Source reductions may shift dominant growth pathways	Multipollutant control of SO_2, NO_x, VOCs, and NH_3 is needed

6. Conclusion and Future Perspectives

The dynamics of aerosol nanoparticle growth have become a critical concern for understanding urban air quality in China's megacities. This review has demonstrated that nanoparticles are not only a small portion of atmospheric aerosols but also a highly dynamic component that connects the chemistry of precursor gases, aerosol microphysics, haze formation, human exposures, and pollution management. The significance of their formation is not in their initial formation, but in their ability to remain alive, grow, and age into optically active, chemically active, and toxicologically significant particle populations. This growth process is particularly significant in Chinese megacities, where anthropogenic emissions, regional transport, and meteorological complexity interact strongly.

One of the main conclusions of this review is that nanoparticle growth is a multistage, multiscale process. Early growth is regulated by the presence of low-volatility vapors and by the ability of newly formed particles to avoid intense scavenging by already-formed aerosols. Future growth is determined by complex combinations of sulfur-based compounds, oxidized organics, nitrate-related species, and multiphase processes that vary across cities, seasons, and pollution regimes. The findings show that no single mechanism can explain the behavior of nanoparticles across all Chinese megacities. Particle growth, instead, is a product of the interactions of source structure, atmospheric chemistry, urban form, the evolution of the visage of the boundary layer, the humidity, and the regional transport.

The other key lesson is that nanoparticle development provides a cohesive framework for understanding the shift from ultrafine-particle pollution to PM2.5 pollution. In most instances, what separates a transient particle-number event from an episode of severe haze is not the intensity of emissions, but the effectiveness with which nanoparticles are expanded into larger, more enduring size modes. This point of view assists in understanding why particle number, particle mass and health risk are not always changing in line with each other. It also explains why a significant improvement in PM2.5 mass concentration does not necessarily mean that nanoparticle-related air quality issues have been eliminated.

An additional aspect of the review is that stronger integration between modeling and observation should be pursued. The high-time-resolution particle sizing, chemical characterization of aerosols and precursor vapors, and box and chemical transport modeling have made significant strides. Nevertheless, significant uncertainties remain in the most primitive stages of development, in the modeling of urban organic chemistry, in multiphase processing, and in the connection between local-scale microphysics and regional atmospheric transport. The next steps in this direction will require multicity observations, unified analytical guidelines, and models that better reflect the relationships between molecular-scale growth processes and air quality outcomes at the city and regional scales.

Policy-wise, the results of this review indicate that air quality management in Chinese megacities should no longer remain a mass-based system. PM2.5 will continue to play a critical regulatory role; however, long-term effective control will increasingly focus on particle counts, precursor mixtures, and the atmospheric processes that transform emissions into sustained particulate pollution. It will be particularly crucial to coordinate control of sulfur dioxide, nitrogen oxides, volatile organic compounds, and ammonia, as well as to cooperate at the regional level among major urban agglomerations. Policymaking must be assessed not only by the effects of policies on emitted pollutants but also by their influence on the survival, growth, and aging of nanoparticles in atmospheric pathways.

Altogether, the dynamics of aerosol nanoparticle growth form the basis of the changing air pollution scenario in Chinese megacities. They are the process-level relationships among the sources of emissions, atmospheric transformation, and environmental impact. The dynamics will be better understood and thus interpreted more scientifically, thereby aiding more effective, process-based approaches to protecting aerosol quality in urban areas. With China still moving towards a cleaner urban environment, nanoparticle research will remain an important frontier in atmospheric research and in policies that benefit public health.

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