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REVIEW ARTICLE

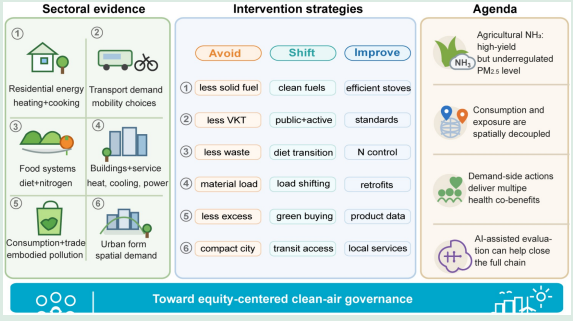
Demand-side pathways for clean air and health

Zhanxiang Wang[1,2], Dong Xie[1,2], Lianming Zheng[1,2], Ruibin Xu[1,2], Yanxing Wu[1,2], Mengyuan Chu[1,2], Huizhong Shen ✉ [1,2]

1. State Key Laboratory of Soil Pollution Control and Safety, Shenzhen Key Laboratory of Precision Measurement and Early Warning Technology for Urban Environmental Health Risks, School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China
2. Guangdong Provincial Observation and Research Station for Coastal Atmosphere and Climate of the Greater Bay Area, Southern University of Science and Technology, Shenzhen 518055, China

HIGHLIGHTS

- Demand-side choices shape emissions, exposure, health, and inequality.
- Consumption-based accounting reveals displaced clean air burdens.
- Demand-side measures deliver health co-benefits beyond cleaner air.
- AI-assisted full-chain evaluation can support equity-centered policy.



ABSTRACT: Conventional air pollution governance relies heavily on supply-side and end-of-pipe controls. While these measures have substantially reduced SO_2, NO_x, and primary particulate emissions, their marginal returns are diminishing. The remaining pollution burden is shifting toward nitrogen-containing secondary aerosols and ozone. This review synthesizes evidence delineating the pathways through which demand-side interventions across diverse sectoral domains (e.g., residential energy, transport, food systems and agriculture, buildings, consumption, and urban form) shape pollutant emissions, ambient concentrations, population exposure, and health outcomes. Three conclusions emerge from this literature review. First, agricultural ammonia is the most cost-effective remaining target for global $PM_{2.5}$ mitigation, yet it remains largely unregulated despite high benefit-to-cost ratios. Second, consumption distribution is increasingly decoupled from actual population exposure across spatial scales. Consequently, consumption-based accounting is a necessary complement to effective air quality governance, not merely a peripheral accounting exercise. Third, demand-side measures generate multipathway health co-benefits through physical activity, healthier diets, reduced indoor exposure, and improved energy security. These benefits often exceed mitigation costs and cannot be captured through production-side regulation alone. Future evaluations must trace the full analytical chain from final demand through nonlinear atmospheric chemistry to health outcomes and inequality, with artificial intelligence positioned as a central methodological priority.

✉ Corresponding author. E-mail: shenhz@sustech.edu.cn

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1 Introduction

Air pollution remains a leading global environmental health threat. Ambient exposure to fine particulate matter ($PM_{2.5}$) causes an estimated 3.3–4.2 million premature deaths annually (Lelieveld et al., 2015; Chowdhury et al., 2022), with even higher mortality attributed to fossil-fuel-derived $PM_{2.5}$ estimated by a dose-response function from the meta-analysis (Vohra et al., 2021). These health burdens fall disproportionately on South and East Asia. Meanwhile, household air pollution from solid-fuel combustion caused an estimated 3.9 million premature deaths in 2010, predominantly in low- and middle-income nations (Smith et al., 2014; IEA, 2024). In response to these compounding health crises, four decades of regulation, including the U.S. Clean Air Act (EPA, 1997), the EU Ambient Air Quality Directive (EU, 2008; EEA, 2025), and China's clean air actions (State Council of the People's Republic of China, 2013; Geng et al., 2024), demonstrate that stringent end-of-pipe and supply-side controls can substantially reduce conventional air pollutants. China's sharp $PM_{2.5}$ reductions during 2013–2020 illustrate this capacity at the national scale (State Council of the People's Republic of China, 2013). Source-specific studies confirm that these gains were primarily driven by industrial, residential, boiler, and vehicle emission controls (Cheng et al., 2019; Zhang et al., 2019).

Two interlocking trends erode the marginal returns of supply-side abatement. First, the remaining $PM_{2.5}$ pollution is shifting from primary particles and sulfate-rich aerosols toward nitrate-, ammonium-, and organic-rich secondary aerosols. These are formed from nitrogen oxides (NO_x), ammonia (NH_3), and volatile organic compounds (VOCs) emitted by dispersed sources, including agriculture, residential energy, urban transport, and supply chains (Gu et al., 2021; Zhang et al., 2026b). As sulfur dioxide (SO_2) controls took effect, the fraction of $PM_{2.5}$ exposure attributed to nitrogen-related precursors globally increased from 30% in 1990 to 39% in 2013 (Gu et al., 2021). Nevertheless, agricultural NH_3 remains comparatively underregulated, despite global assessments indicating that mitigation benefits far exceed implementation costs (Gu et al., 2021; Zhang et al., 2026b). Second, ozone (O_3) pollution has risen or remained severe where $PM_{2.5}$ has declined, particularly in China. This trend stems from nonlinear NO_x–VOC chemistry and aerosol–radical feedbacks that complicate conventional regulation (Li et al., 2018; Lu et al., 2018b; Wang et al., 2020b; Shen et al., 2021c). While average $PM_{2.5}$ concentrations across China's 339 prefecture-level and higher cities fell to 29.3 μg/m^3 in 2024, and 87.2% of days met good-air-quality criteria, surface O_3 remains a persistent challenge (Ministry of Ecology and Environment of the People's Republic of China, 2025).

Although demand-side measures can successfully reduce O_3 precursors, including NO_x and VOCs, the impact depends heavily on the prevailing chemical regime. In VOC-limited environments, NO_x reductions can increase surface O_3 by weakening NO titration and altering radical chemistry; conversely, in NO_x-limited environments, such reductions generally suppress O_3 formation (Shen et al., 2021c). Consequently, demand-side strategies should be evaluated using regional photochemical sensitivity rather than precursor reduction alone. The next phase of clean air policy must address O_3 and secondary $PM_{2.5}$ precursors from dispersed, mobile, and biologically mediated sources, which are fundamentally shaped by energy use, mobility, diet, consumption, and urban form.

Demand-side mitigation was established as a formal pillar of climate policy in the IPCC Sixth Assessment Report (AR6). The Working Group III report estimates that demand-side measures and new forms of service provision can reduce global end-use greenhouse gas (GHG) emissions across buildings, land transport, and food systems by 40%–70% by 2050, while maximizing air quality co-benefits (Creutzig et al., 2022). Contemporary frameworks organize demand-side interventions into three strategies: avoid (reduce service demand), shift (substitute lower-emission service modes), and improve (improve end-use efficiency or fuel quality) (Creutzig et al., 2022). Unlike supply-side measures that target upstream fuel mixes, production technologies, power generation, and end-of-pipe abatement, demand-side measures act directly on final service demand, user behavior, consumption structures, and spatial infrastructure.

Demand-side air pollutant accounting requires greater spatial and chemical specificity than its GHG counterpart. The resulting health benefits depend entirely on where emissions occur, how pollutants are transported and transformed, and which populations are exposed (Zhang et al., 2017a). Nonlinear atmospheric

chemistry further complicates attribution. For example, reducing NO_x in VOC-limited regimes can increase local O_3 levels (Li et al., 2018), while controlling SO_2 without parallel NH_3 abatement can shift the remaining $PM_{2.5}$ toward nitrate- and ammonium-rich aerosols (Gu et al., 2021). Consequently, equity-relevant attribution must trace final demand through four distinct phases: source emissions, atmospheric transport and transformation, population exposure, and exposure–response functions (Davis and Caldeira, 2010; Peters et al., 2011; Nansai et al., 2021). These unique complexities render demand-side air pollution accounting far more methodologically challenging than tracking CO_2.

This review synthesizes demand-side pathways across six key domains: residential energy, transport, food systems and agriculture, buildings, consumption and trade, and urban form. Specifically, we examine how these pathways alter emissions, ambient pollutant concentrations, population exposure, health co-benefits, and inequality. Rather than executing a systematic review, we conducted a targeted literature search in the Web of Science and Scopus using combinations of terms related to demand-side mitigation, atmospheric chemistry ($PM_{2.5}$, O_3, NO_x, VOCs, and NH_3), and societal impact (health, exposure, and inequality). We prioritized studies based on their relevance to demand-side interventions, quantitative assessment of air quality or health outcomes, methodological rigor, and broader implications for clean air policy. Finally, we paired recent quantitative evidence with seminal conceptual studies that establish the methodological foundations of demand-side analysis.

2 Conceptual framework

2.1 From final demand to health burden

Demand-side interventions operate along a causal chain that links final demand directly to public health burdens (Fig. 1). For instance, demand for warmth, mobility, food, and materials generates emissions directly at the point of use or indirectly through global supply chains. Atmospheric chemistry transforms these emissions into ambient pollutants, which interact with population distributions and activity patterns to determine exposure. Exposure, in turn, produces adverse health outcomes governed by established exposure–response relationships (Dockery et al., 1993; Pope III et al., 2002). Distributional inequalities arise at every stage. Consumption levels vary drastically across income groups and countries, while global supply chains and atmospheric chemistry redistribute the resulting emissions across regional borders (Davis and Caldeira, 2010; Zhang et al., 2017a). Furthermore, exposure varies systematically across racial, ethnic, and socioeconomic demographics, with baseline health disparities further amplifying health risk inequality (Tessum et al., 2019, 2021; Dedoussi et al., 2020). Consequently, equitable demand-side policy must address inequalities in demand, emissions, exposure, and health burdens simultaneously, rather than focusing solely on population-wide averages (Shi et al., 2024; Zheng et al., 2024).

In this review, we distinguish three related concepts. First, final demand comprises the goods and services consumed by households, governments, and other end users that drive upstream production and emissions. Second, consumption-based accounting attributes these emissions to final consumers by tracing them through global supply chains. Third, demand-side mitigation encompasses interventions that alter the quantity, timing, location, or composition of final service demand to reduce emissions, exposure, or health impacts. In essence, demand-side mitigation targets the structural drivers of production and emissions, whereas consumption-based accounting traces their environmental and health consequences.

2.2 Demand-side options across sectors

Demand-side mitigation operates across multiple sectors that differ in their underlying demand drivers, intervention mechanisms, and empirical foundations. We organize this literature into six sectoral domains, covering residential energy, transport, food systems and agriculture, buildings and service demand, consumption and trade, and urban form (Table 1). While the avoid–shift–improve typology applies across these domains, their policy instruments, implementation timescales, and distributional costs and benefits differ substantially. Moreover, the evidence base for these domains has matured unevenly. For instance, the residential energy and transport domains possess the longest evaluation histories and strongest causal evidence. Concurrently, the food systems and consumption domains have advanced rapidly by coupling economy-wide, input–output assessment models with chemical transport models. By contrast, policy attention is outpacing the development of supporting empirical evidence in the buildings and urban form domains. Consequently, effect estimates for different sectoral domains must be interpreted strictly within their specific study design and geographical contexts. Unlike CO_2 effects, air pollution effects are rarely transferable across regions.



Fig. 1 The demand-side air pollution chain.

Table 1 Demand-side air-pollution options

Sectoral domain	Representative options	Strategies	Key pollutants/ precursors[a)]	Principal pathway	Typical co-benefits
Residential energy	Clean heating, clean cooking, appliance efficiency, user behavior	A/S/I	$PM_{2.5}$, SO_2, BC, OC	Reduced combustion emissions	Indoor exposure reduction, thermal comfort
Transport	Public transit, bike sharing, congestion pricing, LEZs, active travel, telework	A/S/I	$PM_{2.5}$, NO_x, VOCs, BC, O_3	Reduced vehicle activity, modal shift, cleaner end-use	Physical activity, injury reduction, reduced congestion
Food systems & agriculture	Dietary shift, food-waste reduction, public procurement	A/S/I	NH_3, $PM_{2.5}$, NO_x	Reduced livestock manure and fertilizer demand	Diet-related NCD reduction, land and water gains
Buildings & service demand	Building materials, smart controls, deep retrofits, demand response	S/I	NO_x, $PM_{2.5}$, VOCs, CO, indoor $PM_{2.5}$	Embodied emissions in materials, load shifting	Energy security, comfort, grid flexibility
Consumption & supply chains	Material efficiency, product longevity, e-commerce design	A/S/I	Multiple pollutants across supply chains	Embodied emissions in goods and logistics	Resource use, trade equity
Urban form & population	Compact cities, service co-location, land-use planning, migration	A/S	Multiple pollutants via activity redistribution	Reduced VKT, redistribution of population vs emission field	Walkability, access, reduced exposure inequality

Notes: a) Listed species include directly emitted pollutants and precursors linked to conventionally regulated ambient pollutants, including $PM_{2.5}$, O_3, NO_x, SO_2, and CO. Emerging contaminants that are not routinely monitored or consistently regulated, despite potential health impacts, are not included. Abbreviations: A, avoid; S, shift; I, improve; BC, black carbon; LEZ, low-emission zone; NCD, noncommunicable disease; OC, organic carbon; VOCs, volatile organic compounds; VKT, vehicle-kilometers traveled.

2.3 Uncertainty along the demand-to-health assessment chain

Demand-side air pollution studies are rarely directly comparable owing to cascading uncertainties across the demand-to-health assessment chain. First, emission estimates depend heavily on activity data, emission factors, technology adoption, fuel quality, and spatiotemporal allocation, particularly for dispersed household, traffic, agricultural, and informal-consumption sources. Second, chemical transport models introduce uncertainty when translating precursor emissions into $PM_{2.5}$ and O_3 concentrations and population exposure, driven by regional variations in nonlinear chemistry, meteorology, model resolution, and source–receptor relationships. Third, health-impact estimates are sensitive to exposure–response functions, baseline mortality, population vulnerability, and risk extrapolation at extreme concentrations. Finally, consumption-based estimates are sensitive to multiregional input–output (MRIO) database structures, sectoral aggregation, trade allocation, price harmonization, and the treatment of domestic versus imported emissions. These uncertainties vary by sectoral domain. For instance, residential energy and transport interventions often yield strong localized causal evidence, whereas food system and consumption-based strategies offer broad system coverage but introduce greater model-chain uncertainty. Consequently, this review compares the direction and relative magnitude of effects, consistency across methods, and reported uncertainty propagation or sensitivity analyses, rather than treating raw numerical estimates as directly interchangeable.

3 Sectoral evidence

The six domains outlined in Table 1 differ substantially in empirical maturity. We evaluate each domain through a standardized framework: sectoral domain, representative options, intervention strategies, key pollutants, principal pathway, typical co-benefits. Effect sizes are reported alongside their specific study designs and geographical contexts.

3.1 Residential energy

3.1.1 Clean heating in northern China

Few demand-side interventions have been evaluated as intensively as China's residential clean heating program. Launched in 2017 to eliminate dispersed coal use in northern households, the policy subsidized transitions to natural gas, electric heating, district heating, or biomass pellets (National Development and Reform Commission et al., 2017). Song et al. (2023) attributed an annual $PM_{2.5}$ reduction of 1.9 μg/m^3 during 2015–2021 to this initiative, potentially avoiding 23556 premature deaths in 2021 alone. A city-level cost–benefit analysis across the "2 + 26" region estimated health-economic gains of approximately 109.85 billion yuan, substantially exceeding abatement and subsidy costs. However, localized benefits remained highly uneven (Feng et al., 2021). Household surveys in Jincheng revealed that coal-to-gas conversion nearly doubled heating expenditures, and achieving a 40% particulate matter (PM) emission reduction required an operating-cost compensation of approximately 3.56 yuan/m^2 per month (Yan et al., 2020). Furthermore, winter heating remained responsible for a 4.6 μg/m^3 increase in annual $PM_{2.5}$, illustrating the scale of the demand-side opportunity and the persistence of dispersed household combustion as a pollution source (Song et al., 2023).

By contrast, Krakow, Poland, adopted an aggressive, mandate-driven regulatory model. Rather than offering technology-switching subsidies, a citywide anti-smog resolution prohibited residential coal and wood combustion. An ex-post evaluation attributed reductions of 23%–39% in annual mean PM_{10}, 23%–36% in $PM_{2.5}$, and 39%–41% in particle-bound benzo[a]pyrene directly to the policy, with the largest air quality improvement achieved during the heating season (Herman et al., 2025). These cases demonstrate that different policy instruments can deliver substantial public health benefits. However, the design must balance local affordability, enforcement capacity, and immediate access to clean energy alternatives.

3.1.2 Clean cooking and household air pollution

Transitioning to clean cooking represents a critical residential demand-side pathway for reducing household air pollution, a leading global environmental health risk (Smith et al., 2014). Highlighting this technical potential, the international PURE-AIR study across 120 rural communities identified a distinct fuel gradient in kitchen $PM_{2.5}$ concentrations: 45 μg/m^3 for gas, 53 μg/m^3 for electricity, 92 μg/m^3 for charcoal, and 109 μg/m^3 for wood. Nevertheless, 39% of the surveyed 2541 households practiced fuel stacking (i.e., the continued use of traditional biomass alongside cleaner alternatives) (Shupler et al., 2020). Evidence from China identified a complementary constraint. Continued use of traditional biomass alongside clean

energy substantially attenuated the expected exposure reductions, indicating that the climate and health benefits depend on displacing the baseline polluting technology rather than on simple adoption (Grieshop et al., 2011; Shen et al., 2021a). Conversely, the HAPIN randomized controlled trial demonstrated that sustained support can overcome these barriers. Providing liquefied petroleum gas (LPG) stoves paired with free fuel refills, stove repairs, and behavioral assistance reduced $PM_{2.5}$ exposure among pregnant women by 66% relative to controls (Johnson et al., 2022).

However, recent evidence from the CLEAN-Air program complicates the conventional narrative that LPG transitions automatically deliver clean air (Shupler et al., 2024). In Eldoret, Kenya, kitchen $PM_{2.5}$ concentrations among charcoal users were five times higher than those of LPG users (297 vs. 61 μg/m^3). Conversely, in Obuasi, Ghana, the difference was only 4 μg/m^3 because ambient outdoor pollution overwhelmed indoor gains (Shupler et al., 2024). Consequently, clean-cooking policies should be evaluated by the sustained displacement of polluting fuels and measured exposure reductions rather than nominal stove or fuel adoption rates.

3.1.3 Affordability, fuel stacking, and sustained use

The overarching lesson from clean-heating and clean-cooking research is that equipment adoption does not guarantee sustained clean energy use. Inadequate operating subsidies or limited affordability can cause households to resume coal use for supplementary heating during cold spells (Yan et al., 2020; Feng et al., 2021). Similarly, households with limited access to LPG may continue using charcoal for high-intensity meals or during financial stress (Shupler et al., 2024). Consequently, residential demand-side policies must be evaluated beyond installation rates and emission factors. Instead, assessments must consider clean-fuel costs relative to household income, subsidy persistence, and fuel security during climatic or economic shocks. Conventional evaluations rarely capture these dynamics because continuous, large-scale monitoring of household fuel use and personal exposure remains methodologically difficult. Artificial intelligence (AI)-assisted models can help bridge this gap by integrating heterogeneous datasets to estimate otherwise unobserved patterns of energy use and exposure. For example, Song et al. (2023) combined machine-learning-based weather normalization with causal inference to isolate the $PM_{2.5}$ benefits of China's clean heating program. Similarly, Hill et al. (2019) utilized Super Learner ensembles to predict personal $PM_{2.5}$ exposure during a rural cookstove intervention in Laos using kitchen concentrations, ambient pollution, meteorology, and household characteristics. Scaling these AI-driven approaches can shift policy evaluations from simple equipment tracking toward verifying sustained fuel displacement and realized exposure reductions.

3.2 Transport demand

3.2.1 Public transport and modal shift

Early cross-city research established urban form as an important, although nondeterministic, influence on travel demand. Newman and Kenworthy linked urban structure directly to automobile dependence (Newman and Kenworthy, 1989), while Cervero and Kockelman identified density, diversity, and design as the key physical determinants of trip generation and model choice (Cervero and Kockelman, 1997). Recent studies have strengthened causal inference by exploiting discrete transport interventions. For instance, subway openings provide a useful natural experiment because they occur on fixed dates across cities with otherwise comparable baselines. Using daily $PM_{2.5}$ observations and a regression discontinuity design, Lu et al. (2018a) estimated that new subways in Chinese cities reduced $PM_{2.5}$ concentrations by approximately 18 μg/m^3 through displaced road traffic. Bike-sharing programs produced smaller but more spatially distributed effects: a staggered difference-in-differences analysis of platform entries across multiple cities yielded an average $PM_{2.5}$ reduction of 3.83 μg/m^3 (Cao et al., 2023). Across these evaluations, the environmental benefits scaled linearly with the volume of displaced motor vehicle activity.

3.2.2 Congestion pricing and low-emission zones

Recent studies confirm the efficacy of price- and access-based transport policies. For instance, using a quasi-experimental, monitor-based design, Fraser et al. (2025) found that New York City's (NYC) Congestion Relief Zone reduced daily maximum $PM_{2.5}$ within the cordon by 3.05 μg/m^3 within months of implementation, representing an approximately 22% decline relative to the counterfactual mean. Utilizing comparative interrupted time-series models, Bruyneel et al. (2025) found that pollutant concentrations declined significantly faster within and around low-emission zones (LEZs) in Antwerp and Brussels than in control cities. Crucially, this intervention narrowed

socioeconomic disparities in black carbon (BC) and NO_2 exposure. By contrast, earlier European syntheses reported smaller, highly variable effects where LEZ designs were weaker or compliant alternatives were limited (Holman et al., 2015). Consequently, while price and access instruments can deliver rapid ambient improvements and reduce exposure inequalities in transit-rich cities, they may face political resistance and impose net welfare losses on low-income drivers where practical substitutes for private cars are absent.

3.2.3 Active travel and health co-benefits

Demand-side transport policies often generate larger public health gains through increased physical activity than through reduced ambient air pollution alone. For instance, in comparative 2030 scenarios combining active travel with low-carbon vehicles, Woodcock et al. (2009) found that this strategy averted 7439 and 12995 disability-adjusted life years (DALYs) in London and Delhi, respectively, with physical activity responsible for the majority of these gains. Across European cities, the systemic health benefits of cycling and walking generally exceed the localized harm of inhaling pollution by an order of magnitude, even under moderate ambient pollution (Rojas-Rueda et al., 2016). Globally, the monetized avoided-mortality co-benefits under Paris-aligned climate pathways reached 54–2100 USD/t of CO_2 avoided, often exceeding direct mitigation costs (Markandya et al., 2018). Consequently, transport interventions with modest air quality benefits can yield substantial aggregate welfare gains through multiple parallel health pathways. Analytical models restricted to $PM_{2.5}$ systematically undervalue the true societal returns of active travel.

3.2.4 Telework and demand-side mobility reorganization

Telework serves as a distinct demand-side mobility intervention, yet empirical evidence mapping its direct impact on air quality remains limited. In a systematic review evaluating the sector's broader climate footprints, Hook et al. (2020) found that ~66% of empirical studies reported net emission reductions; However, the same literature reported a substantial rebound effect: residential energy use and non-commuting travel often offset 25%–50% of the gross commute-displacement benefits.

3.2.5 Aviation demand and high-income mobility footprints

Aviation combines exceptionally high carbon intensity per passenger-kilometer with geographically dispersed air pollution effects. Cruise-altitude NO_x contributes substantially to O_3 and $PM_{2.5}$ formation far from urban centers. Eastham and Barrett estimated that global aviation emissions cause approximately 16000 premature deaths annually—6800 from O_3 and 9200 from $PM_{2.5}$—driven predominantly by high-altitude NO_x emissions rather than airport-proximate emissions (Eastham and Barrett, 2016). A subsequent 50-km-resolution GEOS-Chem reassessment of 2015 emissions adjusted these estimates upward, attributing approximately 53100 O_3- and 21200 $PM_{2.5}$-related deaths annually to the sector. These sharp increases were driven primarily by updated epidemiological modeling that incorporated wintertime O_3 effects (Eastham et al., 2024). To address these impacts, route-level inventories derived from Automatic Dependent Surveillance-Broadcast (ADS-B) trajectories enable flight-specific attribution. These data reveal substantial variations across routes, aircraft and operating conditions, allowing targeted demand-side interventions to isolate high-intensity flights (Han et al., 2025). Furthermore, aviation demand is highly concentrated: approximately 1% of the global population generates half of all commercial passenger aviation CO_2 emissions, making per-capita and equity-weighted accounting particularly important for effective governance (Gössling and Humpe, 2020).

3.3 Food systems and agriculture

3.3.1 Agricultural NH_3 as an underregulated $PM_{2.5}$ precursor

Agricultural NH_3 has emerged as a high-priority target for $PM_{2.5}$ mitigation. Global atmospheric chemistry simulations indicate that NH_3 abatement is more cost-effective than NO_x controls for reducing ambient $PM_{2.5}$ because abundant residual NH_3 sustains ammonium nitrate formation across heavily polluted regions (Gu et al., 2021). In China, reducing agricultural NH_3 emissions by 38%–67% was estimated to lower $PM_{2.5}$ levels by 8%–20%, avoiding 90000–240000 premature deaths annually and yielding 18–42 billion USD in net societal benefits against 6–11 billion USD in abatement costs (Zhang et al., 2020). A recent international assessment spanning 185 countries estimated that a suite of 32 target measures could reduce global NH_3 emissions by up to 60%. This strategy would generate 722 ± 302 billion USD in environmental, health, and resource benefits at a cost of 274 ± 116 billion USD, with China and India capturing the largest net gains (Zhang et al., 2026b).

Production-based inventories attribute these emissions directly to livestock manure management and synthetic fertilizer applications (Zhang et al., 2017b, 2020). Conversely, a demand-side perspective traces them to animal-source food consumption and market demand for fertilizer-intensive cereals (Erisman et al., 2008; Galloway et al., 2008). However, this spatial and structural dispersion creates two severe regulatory challenges. First, unlike SO_2 and NO_x from large centralized utilities, emissions from thousands of individual farms and barns cannot be controlled using the standardized equivalent of smokestack scrubbers. Second, agricultural NH_3 remains entirely absent from major ambient air quality standards, including China's GB 3095 standards and the USA's National Ambient Air Quality Standards, leaving its mitigation potential largely unexploited.

Production-side interventions focus on limiting fertilizer and manure losses via precision nitrogen management, enhanced-efficiency fertilizers, improved animal housing, covered or acidified manure storage, and direct soil injection (Bittman et al., 2014; Zhang et al., 2020; Zhang et al., 2026b). While indispensable, the deployment of such interventions is heavily constrained by farm scale, upfront capital costs, advisory capacity, and the difficulty of monitoring compliance across diffuse agricultural land. Demand-side measures bypass these bottlenecks by reducing the demand for livestock production, feed grains, and nitrogen-heavy crops. The empirical literature identifies three primary demand-side mechanisms. First, plant-forward diets could avert 108000–236000 premature deaths and increase economic output by 0.6–1.3 trillion USD through cleaner air and improved labour productivity (Springmann et al., 2023). Second, eliminating food loss and waste could reduce food production–related NH_3 emissions by 11.4 Tg (16%), lower local $PM_{2.5}$ concentrations by up to 5 μg/m^3, and reclaim 1.5 million $PM_{2.5}$-related life years (Guo et al., 2023). Third, leveraging public standards to shift aggregate demand without relying solely on individual behavior. By reducing upstream nitrogen throughput, these demand-side measures systematically lower farm-level abatement requirements and costs while aligning nitrogen management with public health objectives (Springmann et al., 2018; Willett et al., 2019).

3.3.2 Dietary transitions and $PM_{2.5}$-related health benefits

Early sustainability assessments established that animal-source foods place a disproportionate burden on environmental systems, with livestock occupying 83% of agricultural land and generating 60% of food-system GHG emissions despite supplying only 18% of calories globally (David and Marcia, 2003; Poore and Nemecek, 2018). Subsequent life-cycle and atmospheric chemistry analyses have quantified the air quality benefits of dietary shifts. For example, adopting national dietary guidelines in China (i.e., reducing red and processed meat intake while increasing vegetable consumption) was estimated to lower NH_3 levels by approximately 17%, reduce $PM_{2.5}$ concentrations to 2–6 μg/m^3, and avoid 75000 premature deaths annually (Liu et al., 2021). Globally, transitioning to plant-forward diets could avoid approximately 108000, 188000, and 236000 premature deaths under flexitarian, vegetarian, and vegan scenarios, respectively, primarily through reduced ambient $PM_{2.5}$ exposure (Springmann et al., 2023). Without combining these dietary changes with aggressive technological improvements and food-waste reductions, food system environmental pressures are projected to increase by 50%–90% between 2010 and 2050, threatening several critical planetary boundaries (Springmann et al., 2018; Willett et al., 2019).

Recent literature has extended this demand-side framework to international trade networks. Food production caused an estimated 840400 $PM_{2.5}$-attributable deaths globally in 2017, with approximately 11% (94100 deaths) linked to the international food trade, which represents a statistical economic value of 3.15 trillion USD (Xing et al., 2026). Trade routing can amplify or mitigate these health burdens. For instance, shifting exports from sparsely to densely populated regions avoided 44900 deaths, demonstrating that air quality impacts depend heavily on where food is produced and how trade is routed. Complementing these global trade dynamics, micro-level household data reveal stark socioeconomic disparities: lower-income households experience greater pollution exposure per unit of consumption yet face the most severe financial constraints when attempting to adopt low-impact diets. Without targeted structural support, these inequalities will likely widen despite declining aggregate global emissions (Zheng et al., 2024).

3.3.3 Food waste, public procurement, and nitrogen management

Approximately one-third of global food production is lost or wasted, generating avoidable NH_3 and NO_x emissions from food that is never consumed (Guo et al., 2023). Demand-side mitigation can reduce these emissions by avoiding unnecessary production and shifting consumption towards lower-emission diets. AI-assisted forecasting can strengthen the first pathway by aligning production more closely with demand. For example, the Foodforecast machine-learning system

reduced bakery returns by approximately 30%, while its environmental benefits exceeded the operational impacts of the system by one to three orders of magnitude (Hübner et al., 2024). Public procurement can also reshape demand at scale without relying solely on individual behaviour. In a Swedish municipality, animal-source foods generated 76% of food-service emissions, and replacing red meat in only 6% of purchased food by weight could reduce greenhouse-gas emissions by up to 44% (Kjellberg et al., 2024). More directly relevant to nitrogen, an analysis of Spanish school lunches attributed 92.6% of their nitrogen footprint to food production and estimated that replacing beef with non-meat proteins could reduce the total footprint by 76% (Martinez et al., 2022). These demand-side measures complement production-side interventions, including variable-rate fertilizer application, manure incorporation and cover cropping, which rank among the most cost-effective options for reducing agricultural emissions globally (Zhang et al., 2026b). AI can further support farm-level mitigation by integrating field, weather and management data to optimize fertilizer recommendations, although performance remains sensitive to algorithm choice and input variables (Tanaka et al., 2024).

3.3.4 Equity and nutritional constraints

Evidence for the efficacy of dietary shifts is strongest for high-income countries but cannot be universally transferred to low- and middle-income nations. In these settings, animal-source food intake remains nutritionally inadequate and livestock support rural livelihoods (Springmann et al., 2018; Willett et al., 2019). Consequently, food policy should be region-specific. Where livestock production is concentrated in industrial operations and animal-source food intake meets or exceeds nutritional guidelines (e.g., in much of North America, Europe, and increasingly East Asia), dietary shifts offer substantial potential for mitigating agricultural NH_3. Where livestock are dispersed and intake remains inadequate (e.g., in much of sub-Saharan Africa and parts of South Asia), reducing animal-source food consumption should not be prioritized. This regional asymmetry must serve was a central design principle for integrating global food systems into air quality governance.

3.4 Buildings and service demand

3.4.1 Heating and cooling demands as emerging drivers of urban emissions

Historically, buildings have been treated as a climate policy issue rather than an air quality concern. This stems from the assumption that their emissions are minor relative to those from transport and industry, or that they are displaced by district heating and clean electricity networks. However, empirical evidence from cities with advanced supply-side emission control challenges this view. In central London, eddy covariance measurements during 2021–2023 attributed 72% ± 17% of localized NO_x emissions to natural gas boilers. This relative contribution expanded as road transport NO_x declined under successive expansions of the Ultra Low Emission Zone (Cliff et al., 2025). Under the Clean Heat Program in NYC, which phased out No. 6 residual heating oil, the conversion of every ten buildings within a census tract was associated with mean reductions of 0.28 ppb SO_2, 0.12 μg/m^3 $PM_{2.5}$, and 0.29 ppb NO_2 (Zhang et al., 2021). China may be undergoing a parallel transition. Under China's "2+26" clean heating program, replacing residential coal with gas and electricity substantially reduced SO_2 and primary PM emissions (Song et al., 2023). Gas-fired boilers and electricity generation now account for a growing share of the residential NO_x footprint amid rising heating and cooling demands. As transport and industrial emissions decline, dense building stocks and localized heating systems may emerge as dominant urban pollution sources, transforming them into primary targets for demand-side air quality governance.

3.4.2 Smart controls, retrofits, and demand response

Energy-efficient and flexible buildings are central to demand-side climate mitigation, yet their air quality effects remain poorly characterized. High-level modeling by the International Energy Agency (IEA) estimates that high-performance construction and renovations can reduce sector-wide energy use by approximately 30% by 2050 (IEA, 2019). The Low Energy Demand scenario projects that efficiency improvements, digitalization, and building retrofits will reduce final energy demand to 245 EJ/yr by 2050, representing a reduction of 40% (Grubler et al., 2018). London boiler measurements indicate that this omission reflect limited measurement rather than negligible emissions (Cliff et al., 2025), but the air-quality effects of low-energy-demand scenarios have yet to be evaluated independently at high spatial resolution. In the USA, ambitious but feasible efficiency upgrades were projected to reduce $PM_{2.5}$ and CO_2 emissions by 18%–25% and 6%–11% by 2050, respectively, although the indoor air benefits depended on the presence of adequate ventilation (Gillingham et al., 2021). Nevertheless, most building-energy studies

evaluate only energy use or CO_2 emissions, leaving the corresponding shifts in atmospheric chemistry, outdoor concentrations, and population exposure unresolved. Crucially, the broader air quality effects of low-energy-demand scenarios have yet to be evaluated independently at a high spatial resolution. Consequently, low-energy-demand building strategies cannot be evaluated independently through carbon metrics alone. Maximizing their societal returns will require an integrated evaluation of emissions, atmospheric chemistry, and exposure.

3.4.3 Interactions with power sector emissions

Building electrification, particularly through heat pump adoption, illustrates the tight coupling between demand-side interventions and supply-side energy systems. While replacing onsite combustion eliminates local boiler emissions, the net air quality benefits depend on where and when the additional electricity is generated. Empirical evidence from China demonstrates that electric heating can shift emissions from households to the power sector. This shift attenuates $PM_{2.5}$ reductions when marginal generation is coal-fired but strengthens air quality and climate benefits as the grid decarbonizes (Wang et al., 2020a; Yang et al., 2023). Conversely, in grids with high renewable energy penetration, such as parts of California and Western Europe, low-carbon generation easily absorbs this additional heating demand, substantially reducing fossil fuel use and its associated emissions (Brockway and Delforge, 2018; Pehle et al., 2025).

The public health returns of these spatial dynamics are substantial but uneven. Under a 2050 decarbonization scenario in California, a building-electrification pathway reduced population-weighted $PM_{2.5}$ more than a truck-electrification pathway, avoiding an estimated 6100 deaths statewide. However, these health gains varied markedly across counties and socioeconomically disadvantaged communities (Zhu et al., 2022). Industrial heat transitions exhibit similar spatial dependence, where facility locations, process routes, and nearby population distributions dictate the health benefits of fuel substitution. For example, an adjoint-based analysis across 5194 Chinese iron and steel plants revealed large inter-plant heterogeneity in marginal health damages per ton of output (Zhang et al., 2026a). Ultimately, electrification yields the greatest air quality dividends when the additional power generation is clean and policy designs explicitly integrate the spatial distribution of emissions and population exposure.

3.5 Consumption, trade, and embodied air pollution

3.5.1 Consumption-based air pollution accounting

Coupling MRIO analysis with chemical transport and health-impact models has shifted the attribution of pollution-related mortality from point-source producers to final demand. This methodology builds on Leontief's foundational integration of environmental repercussions into input–output frameworks (Leontief, 1970), which underpins contemporary global multisectoral pollution accounting. Applying this framework to China, Zhao et al. (2019) attributed approximately 1.08 million $PM_{2.5}$-related premature deaths in 2012 to final demand. A granular breakdown of these consumer-driven fatalities revealed that direct household fuel use was responsible for 20% of the total mortality burden, emissions embodied in household consumption were responsible for an additional 24% of these deaths, and government expenditure, capital investment, and exports accounted for the remainder (Zhao et al., 2019). Consequently, even when households abandon direct fuel combustion, their purchases continue to drive substantial pollution-related mortality through upstream supply chains.

3.5.2 International trade and transboundary health burdens

The transboundary nature of air pollution has long shaped its international governance. Historically, documentation on acid rain from SO_2 and NO_x helped motivate agreements such as the 1979 Convention on Long-Range Transboundary Air Pollution (Likens and Bormann, 1974). Modern consumption-based mortality accounting extends this principle from atmospheric transport to emissions physically embodied in global trade, which imposes larger and more unequal cross-border health burdens than atmospheric transport alone. For instance, among 3.45 million $PM_{2.5}$-related deaths globally in 2007, 12% (411100) occurred downwind of the emitting region, while 22% (762400) were associated with goods consumed outside the producing region (Zhang et al., 2017a). This consumer-driven decoupling creates stark geographical disparities. For example, Chinese emissions caused more than 3100 premature deaths in Western Europe and the USA, while consumption in these regions contributed to more than 108600 deaths in China. Furthermore, Chinese production of American goods measurably degraded ambient air quality in the western USA (Lin et al., 2014). Meanwhile, aggregate G20 consumption drove an estimated 1.98 million $PM_{2.5}$-related deaths globally

in 2010, including 78600 infant deaths, which is equivalent to one premature death attributed to the lifetime consumption of 28 residents (Nansai et al., 2021). Wiedmann and Lenzen (2018) review the broader environmental consequences of international trade.

Beyond final consumption, capital export networks redistribute emissions and health burdens via pollution-intensive infrastructure. An analysis of overseas coal-fired power plants revealed that the CO_2 footprint of cross-border facilities, alongside co-emitted SO_2, NO_x and PM, is unevenly distributed (Guo et al., 2024). Consumption- and investment-side responsibilities concentrate within a few specific economies, whereas actual population exposure occurs elsewhere. Similar disparities arise within countries: Dedoussi et al. (2020) estimated that 41%–53% of air pollution–related premature deaths in the USA occur beyond the borders of the emitting state. Furthermore, commercial and residential sources caused twice as many cross-state deaths as power generation in 2018.

3.5.3 Household consumption and urban–rural inequality

Demand-side analysis reveals structural inequalities only when evaluated at a sufficiently fine subnational resolution. An adjoint-based assessment of China's construction sector illustrates this localized mismatch (Wang et al., 2026). Life-cycle construction activities, including cement and steel production, logistics, and raw material processing, account for approximately half of China's ambient $PM_{2.5}$-related health burden. This burden is split unevenly between urban and rural populations. Because heavily polluting manufacturing facilities concentrate around peri-urban and rural production facilities, local residents bear the pollution exposure risks, whereas the final construction services flow disproportionately to urban consumers. This subnational separation of emissions directly mirrors the transnational asymmetry in international trade documented by Zhang et al. (2017a) and Nansai et al. (2021).

3.5.4 Digital consumption, e-commerce, and rebound effects

Digital consumption is fundamentally reshaping pollution footprints by altering consumer behavior, yet its net air quality effects remain highly context-dependent. In China, rapid e-commerce growth successfully reduced primary $PM_{2.5}$ emissions because consolidated logistics networks are more efficient than individual shopping trips. However, emissions of secondary $PM_{2.5}$ precursors, including NO_x, SO_2, and VOCs, rose due to increased reliance on air freight and resource-intensive packaging (Xu et al., 2025). Between 2000 and 2023, operational improvements steadily lowered the emission intensities of online retail, whereas those of conventional retail rose alongside consumer car use (Xu et al., 2025, 2026).

Aggregate emission metrics can obscure these pollutant-specific trade-offs, underscoring the need for product-level data (Shahmohammadi et al., 2020; Xu et al., 2025, 2026). AI could help fill these information gaps. For instance, Koyamparambath et al. (2022) combined natural language processing with random forest models trained on environmental product declarations to predict life-cycle global warming, acidification, and photochemical O_3 creation potentials. Although machine learning performance depends strictly on the quality and representativeness of training datasets, these automated screening tools can support procurement and consumption-based accounting by screening potentially high-impact products before comprehensive life-cycle assessments are available.

3.6 Urban form, migration, and spatial redistribution of exposure

3.6.1 Urbanization and household-energy transition

The relocation of approximately 300 million people from rural villages to urban centers between 1995 and 2015 constituted one of the largest demand-side transitions in modern China. Because urban households generally use cleaner fuels for heating and cooking than rural households, this redistribution moderated air pollution even without direct clean air interventions. Shen et al. (2017) estimated that this migration-driven energy transition reduced national-average ambient $PM_{2.5}$ exposure by approximately 4 $\mu g/m^3$ and lowered the associated mortality. These benefits reflect the net effect of opposing changes: lower per-capita emissions from household fuel use and greater population concentration in high-emission urban areas.

3.6.2 Population redistribution and exposure change

Population redistribution shapes air pollution exposure through three analytically distinct mechanisms. First, long-term urbanization and planning alter residential location, access to clean energy and services, and proximity among households, jobs, and pollution sources. China's migration-driven household-energy

transition exemplifies this structural pathway (Shen et al., 2017). Second, daily fluctuations in activity spaces redistribute people within existing urban structures through commuting, shopping, schooling, telework, and recreation (Hook et al., 2020; Song et al., 2024a). While total emissions may remain static, individual exposure shifts with time spent near roadways, in transit, at workplaces, or indoors. Tracking these dynamics requires high-resolution time–activity, mobility, and exposure data rather than residential population maps alone. Third, abrupt societal disruptions reveal how rapid mobility changes can decouple emissions from exposure. During China's 2020 national quarantine, individual-level mobility data and chemical transport modeling revealed that while outdoor $PM_{2.5}$ concentrations declined, actual human exposure increased for a sizeable population because people spent more time indoors, where restricted ventilation and indoor sources dominated the exposure profile (Shen et al., 2021b). Consequently, evaluating population-related interventions requires dynamic assessments of where people live, move, and spend time, rather than a narrow reliance on raw emission inventories or static census data.

3.6.3 Compact urban form and low-emission service provision

Long-term changes in urban form can deliver urban services with lower per-capita air pollution impacts. Compact development successfully reduces vehicle travel and building-energy demand through smaller dwellings and shared walls, while improving public service accessibility (Woodcock et al., 2009; Petrichenko and Vautrin, 2024). However, higher population density can increase human exposure to residual localized emissions, making health benefits contingent on concurrent emission reductions across the transport, buildings, and energy supply sectors. Consequently, urban form interventions must be evaluated over long timescales against shifting emission baselines and dynamic population distributions.

Modern data methodologies can overcome these evaluation challenges. For instance, Yu et al. (2023) coupled multiple data sources with ensemble machine learning to estimate daily global $PM_{2.5}$ exposure from 2000 to 2019, revealing spatial and temporal inequalities beyond ground-monitoring coverage. By combining these machine learning frameworks with localized mobility, land-use, and demographic data, researchers can determine whether compact development, migration, and transit-oriented planning reduce population-weighted health burdens, rather than merely redistributing emissions or improving air quality in selected locations.

3.7 Sector-specific roles of demand- and supply-side mitigation

Demand- and supply-side mitigation are complementary, with their comparative advantages determined by source characteristics, technological maturity, regulatory feasibility, and societal co-benefits. Supply-side interventions, including cleaner fuels, industrial process optimization, and end-of-pipe technologies, are generally most effective for centralized, technologically controllable sources such as power plants, industrial boilers, and large combustion facilities (EPA, 1997; EU, 2008; Geng et al., 2024). By contrast, demand-side measures are vital for dispersed end uses and consumption patterns that are poorly addressed by technological controls alone. Domains such as residential heating and cooking, transport, food systems and agriculture, consumption, and urban form shape emissions directly through behavioral choices and service demand rather than upstream production technologies. In these areas, avoiding demand or shifting consumption may yield durable health benefits while also increasing physical activity, promoting healthier diets, lowering indoor pollution, decreasing energy demand, and improving affordability or resilience (Creutzig et al., 2022).

Feasibility across these domains depends on sector-specific constraints. In residential energy and buildings, demand-side measures excel when cleaner fuels, appliances, retrofits, or electrified heating are affordable and reliable. However, their efficacy is attenuated under fuel stacking or when electrification shifts the emission burden to coal- or gas-fired power systems (Shupler et al., 2020; Feng et al., 2021; Zhang et al., 2021; Johnson et al., 2022; Song et al., 2023). In transport, supply-side standards and fleet electrification are suitable for contexts dominated by high per-kilometer emissions, whereas demand-side measures are more beneficial where congestion, short car trips, and total vehicle-kilometers drive localized exposure in dense cities (Woodcock et al., 2009; Rojas-Rueda et al., 2016; Anenberg et al., 2017; Hook et al., 2020; Zeng et al., 2024; Bruyneel et al., 2025; Fraser et al., 2025). In food systems and agriculture, supply-side NH_3 abatement generally predominates where fertilizer and manure emissions are technically controllable at the farm level, while demand-side dietary, procurement, and food-waste measures are better suited to areas with excess consumption or shiftable institutional demand (Zhang et al., 2020; Gu et al., 2021; Guo et al., 2023;

Springmann et al., 2023; Zhang et al., 2026b). In trade, aviation, and digital consumption, demand-side approaches are particularly valuable when emissions are embodied in supply chains, displaced beyond the consuming jurisdiction, or locked in by long-term urban infrastructure (Zhang et al., 2017a; Nansai et al., 2021; Guo et al., 2024; Xu et al., 2025, 2026). Additionally, policy maturity varies markedly across sectoral domains. Residential energy and transport possess comparatively well-estimated empirical foundations and mature policy instruments. Conversely, interventions targeting agricultural NH_3, consumption-based emissions, digital consumption, and urban form remain less developed and require stronger monitoring, attribution frameworks, and institutional coordination.

As a general principle, supply-side mitigation should remain the primary policy instrument for concentrated sources with mature controls, high-emission rates, and clear regulatory authority. By contrast, demand-side mitigation must be prioritized for dispersed end uses, when supply-side controls face diminishing marginal returns, if avoided demand costs less than an expanded supply system, or when nonair-quality co-benefits raise the social benefit–cost ratio. The most robust environmental strategies combine both approaches: demand-side measures reduce the scale and alter the composition of required energy, mobility, food, material, and spatial services, while supply-side measures meet the remaining demand with low-emission technologies (Table 2).

4 Health co-benefits and distributional inequalities

Empirical evidence across sectoral domains confirms that demand-side measures yield multiple, sector-specific co-benefits. In transport, demand management increases physical activity and reduces road-traffic injuries and noise, with physical activity often generating larger public health returns (measured in avoided DALYs) than reduced ambient $PM_{2.5}$ and NO_2 exposure (Woodcock et al., 2009; Rojas-Rueda et al., 2016). In food systems and agriculture, interventions reduce NH_3-derived $PM_{2.5}$ exposure and lower the incidence of diet-related noncommunicable disease. Crucially, the health gains from adopting plant-forward diets are often comparable to or exceed those achieved through improved air quality alone (Springmann et al., 2018, 2023; Liu et al., 2021). In residential energy, the transition to clean heating reduces indoor exposure and ambient $PM_{2.5}$ while improving thermal comfort (Shen et al., 2021a; Song et al., 2023). Complementary building efficiency measures can lower domestic energy bills while enhancing climate resilience (Cliff et al., 2025).

Distributional inequalities are as consequential as aggregate impacts because the beneficiaries of pollution-generating consumption rarely bear the resulting exposure and health burdens. This systemic asymmetry manifests across three interrelated dimensions: race and ethnicity, income, and space. In the USA, Tessum et al. (2019, 2021) demonstrated that non-Hispanic white populations experience 17% less $PM_{2.5}$ exposure than their consumption causes, whereas Black and Hispanic populations suffer 56% and 63% more exposure, respectively. Income inequality follows a similar pattern. High-income households generate disproportionate pollution footprints through aviation, spacious dwellings, and supply-chain-intensive consumption (National Development and Reform Commission et al., 2017; Gössling and Humpe, 2020; Han et al., 2025). Conversely, lower-income populations are more vulnerable to ambient and household pollution and bear the heaviest economic burdens when demand-side policies raise heating, fuel, or food prices (Shupler et al., 2019; Feng et al., 2021). For example, an adjoint-based analysis of food-system health burdens in China found that lower-income groups bear a higher per-capita exposure-weighted mortality risk despite consuming smaller, less emission-intensive diets on average (Zheng et al., 2024). Structural disparities arise when environmental burdens are displaced across regions through international trade networks (Zhang et al., 2017a; Nansai et al., 2021), cross-state pollution spillovers (Dedoussi et al., 2020), and urban–rural divides (Wang et al., 2026).

The central policy implication is that demand-side air pollution policies should be judged not only by reductions in population-average exposure but also by whether they narrow existing exposure inequalities. Reducing aggregate mortality is necessary but insufficient.

5 Discussion

China's air quality trajectory exemplifies a global inflection point in air pollution governance. Decades of stringent industrial controls, coal-power regulation, and end-of-pipe technologies have successfully suppressed point-source emissions (Cheng et al., 2019; Zhang et al., 2019). However, the remaining pollution burden increasingly originates from dispersed, demand-side

Table 2 Summary of demand-side mitigation options by sectoral domain, including cost and feasibility, benefits, potential, uncertainties, and spatial scope

Sectoral domain	Cost/feasibility	Benefits	Potential	Uncertainties	Scope/ evidence
Residential energy	Most feasible with subsidies, affordable fuels, reliable supply, poverty protection	Lower household air pollution and mortality, warmer homes, less solid-fuel use	China's clean heating program: $PM_{2.5}$ −1.9 μg/m^3, HAPIN LPG: personal exposure ~66% lower	Fuel stacking, backup fuels, affordability shocks, upstream emissions	Household to regional, multicountry evidence
Transport	Requires accessible public transport, safe active-travel infrastructure, public acceptance of pricing	Lower exposure, greater physical activity, less noise, injury risk, congestion	Active-travel scenarios: 7439 DALYs averted in London and 12995 DALYs in Delhi, pricing/LEZs cut local $PM_{2.5}$	Equity, spillovers, rebound travel, and telework-related home energy use	Urban/metropolitan, London, Delhi, Antwerp, Brussels, NYC
Food systems & agriculture	NH_3 controls are cost-effective, dietary shifts fit regions with intake above nutritional needs	Avoided mortality, lower nitrogen deposition, resource savings, health gains	China: NH_3 decreases of 38%–67%, $PM_{2.5}$ lower by 8%–20%, global measures: NH_3 decreases of up to −60%	Nutrition, farmer adoption, livestock livelihoods, fertilizer response, chemical regime	Farm to global, largest net gains in China and India
Buildings & service demand	Depends on retrofit depth, fuel prices, grid mix, ventilation, and building age	Fewer deaths, lower combustion exposure, lower bills, comfort, resilience gains	NYC's Clean Heat Program reduced SO_2, $PM_{2.5}$, and NO_2, US efficiency scenario: $PM_{2.5}$ emissions lower by 18%–25% by 2050	Ventilation, comfort rebound, peak loads, marginal electricity emissions	Building to national, NYC, California, Western Europe
Consumption & supply chains	Costs are shared across consumers, firms, and trade partners; policy levers are indirect	Lower embodied health burdens, clearer responsibility, logistics efficiency gains	Trade: 22% of 3.45 million $PM_{2.5}$ deaths in 2007, G20 consumption: 1.98 million deaths in 2010	MRIO and inventory uncertainty, outsourcing, rebound consumption, air freight, packaging	Global supply chains and logistics, G20, China, cross-border trade networks
Urban form & population	High upfront planning/ infrastructure costs, benefits require coordinated land-use and emission controls	Lower mobility and energy demand, better accessibility, long-run exposure reduction	China household-energy effect: exposure −4 μg/m^3, compact form lowers travel and energy demand	Residual local emissions, density-exposure trade-offs, affordability, land-use lock-in	Urban to national, Chinese migration evidence and urban-form literature

Abbreviations: DALY, disability-adjusted life years; LEZ, low-emission zone.

activities embedded in global supply chains. This shift changes how policy effectiveness must be evaluated. Aggregate emission metrics are no longer sufficient because equivalent quantities of precursor emissions can produce markedly different health effects depending on localized chemical regimes, atmospheric transport, and proximity to exposed populations (Henze et al., 2007, 2009; Anenberg et al., 2017; Zheng et al., 2026). Because secondary $PM_{2.5}$ and O_3 formation involves nonlinear chemistry and regional transport (Li et al., 2018; Lu et al., 2018b; Shen et al., 2021c; Mai et al., 2024), local emission reductions do not yield proportional health gains (Song et al., 2024b). Consequently, policy evaluation must quantify the marginal, exposure-weighted health response to changes in final demand.

Such evaluations require an integrated framework that unifies five historically separated domains: consumer demand and trade, pollutant emissions, atmospheric transport and chemistry, population exposure, and health outcomes and inequality. Existing studies generally examine individual links, including consumption-based emission accounting (Davis and Caldeira, 2010; Peters et al., 2011; Wiedmann and Lenzen, 2018), atmospheric source attribution (Zhang et al., 2017a; Dedoussi et al., 2020), health-impact assessment (Lelieveld et al., 2015; Cohen et al., 2017; Vohra et al., 2021), and environmental inequality (Tessum et al., 2019, 2021; Zhao et al., 2019; Zheng et al., 2024). By connecting household expenditure and activity data, environmentally extended input–output models, high-resolution emission inventories, atmospheric simulations, exposure–response functions, and demographic vulnerability data, this integrated framework would enable cross-sector comparisons while identifying beneficiaries, vulnerable groups, and potential trade-offs.

To alleviate the computational burdens of running fully coupled process-based atmospheric and macroeconomic models, high-order sensitivity analysis, adjoint modeling, and AI must be deployed. Within this integrated framework, AI should complement, rather than replace, process-based atmospheric models by emulating nonlinear chemical responses; assimilating heterogeneous activity, expenditure, remote-sensing, and monitoring data; separating meteorological variability from emission-driven change; and screening policy scenarios. Coupling these machine learning tools

with adjoint sensitivities and causal inference preserves physical interpretability while actually capturing rebound effects and distributional inequalities. Nevertheless, important limitations remain: models trained in one geographical setting may not be transferable to another, prediction accuracy does not establish causality, and black-box models can obscure mechanisms and equity considerations. Furthermore, robust applications require dense, representative, and well-governed datasets. Future studies must benchmark AI against process-based models, prioritize interpretable or theory-guided structures where policy stakes are high, conduct out-of-sample validation, and transparently report uncertainty, data coverage, and computational footprints.

Furthermore, behavioral feedbacks and rebound effects shape demand-side outcomes. As documented across sectoral domains, interventions trigger complex structural rebounds that must be modeled dynamically rather than assumed to be static. For example, high operating costs may encourage households participating in China's clean heating program to retain solid-fuel stoves for supplementary heating, undermining sustained health gains (Feng et al., 2021; Shen et al., 2021a; Song et al., 2023). Additionally, teleworking and e-commerce may reduce passenger travel while increasing freight activity, packaging waste, or consumption frequency (Hook et al., 2020; Jaller and Pahwa, 2020; Shahmohammadi et al., 2020; Xu et al., 2025, 2026). Similarly, increased living space, rising comfort demands, and higher peak electricity loads can erode the benefits of building efficiency upgrades and electrification (Grubler et al., 2018; Petrichenko and Vautrin, 2024; Khanna et al., 2025). Evaluations should consider sustained adoption, measured exposure, infrastructure lock-in, and system-wide feedbacks rather than technology-installation rates or short-term emission changes alone.

Air quality governance directly converges with climate policy, public health, urban systems, and consumption governance. Demand-side interventions, such as plant-forward diets, low-emission mobility, efficient buildings, and reduced material consumption, can lower GHG emissions while maximizing localized public health benefits by improving ambient air quality, household exposure, physical activity, and dietary quality. Policies that neglect these system-wide interactions risk displacing emissions to vulnerable populations, exacerbating subnational inequalities, or forgoing health co-benefits. Consequently, demand-side mitigation must evolve from a peripheral accounting exercise to a core pillar of clean air governance.

CRediT Authorship Contribution Statement

Zhanxiang Wang: Methodology, Investigation, Conceptualization, writing-original draft; **Dong Xie:** Investigation, Validation, Review & editing, Formal analysis; **Lianming Zheng:** Investigation, Review & editing, Formal analysis, Visualization; **Ruibin Xu:** Resources, Investigation, Review & editing; **Yanxing Wu:** Conceptualization, Review & editing, Supervision, Visualization; **Mengyuan Chu:** Conceptualization, Review & editing, Supervision, Visualization; **Huizhong Shen:** Funding acquisition, Resources, Conceptualization, Review & editing, Supervision, Visualization, Project administration

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Author Biography



Huizhong Shen is an Associate Professor in the School of Environmental Science and Engineering at Southern University of Science and Technology. He received his bachelor's degree (2009) and Ph.D. (2014) from Peking University and conducted postdoctoral research at the Georgia Institute of Technology. His research focuses on the driving forces and impacts of global emissions of greenhouse gases and air pollutants. His representative contributions include (1) systematic assessments of the global emissions, atmospheric transport, and lung cancer risks of polycyclic aromatic hydrocarbons; (2) elucidation of how population migration during China's urbanization has affected residential energy transitions, pollutant emissions, air quality, and public health; and (3) evaluation of demand-side solutions for the low-carbon transition and clean air. He is also committed to advancing air-quality modeling as well as forward and adjoint sensitivity analysis for diagnosing severe air-pollution episodes, assessing health impacts, and constraining emissions through inverse modeling. As first or corresponding author, he has published in leading journals, including Nature Climate Change, Nature Geoscience, Nature Human Behaviour, Nature Food, Science Advances, One Earth, and Environmental Science & Technology, with an H-index of 61. He serves on the Editorial Advisory Board of Environmental Science & Technology and the Editorial Board of Environmental Science and Ecotechnology.