Cleaner Production Letters 9 (2025) 100116

Contents lists available at ScienceDirect

Cleaner Production Letters

journal homepage: www.journals.elsevier.com/cleaner-production-letters

Assessing air quality improvements during the 2022 Beijing Winter Olympics: A case for sustainable urban management

Jie Gao [a], Markus Lang [b,*], Yiyi Jiang [a,c]

[a] School of Leisure Sports and Tourism, Beijing Sport University, Beijing, 100084, China
[b] Institute of Sport Sciences, University of Lausanne, Lausanne, 1015, Switzerland
[c] Alberta International School of Recreation, Sport, and Tourism, Beijing Sport University, Hainan, 572423, China

A R T I C L E I N F O

Handling Editor: Dr B Tomás B. Ramos

Keywords:
Olympic Games
Mega-sporting events
Environmental impacts
Air quality
Beijing Winter Olympic Games
Event study

A B S T R A C T

Air pollution remains one of the most pressing environmental challenges facing rapidly urbanizing regions worldwide, threatening public health and sustainable development. Mega-sporting events like the Olympic Games often lead to increased environmental regulation, creating a rare opportunity to implement large-scale air quality management measures. However, whether these short-term interventions result in long-term improvements in urban air quality remains an open question. This study examines whether the 2022 Beijing Winter Olympic Games served as a catalyst for long-term improvements in air quality. Using an event study method, monthly Air Quality Index data were analyzed to estimate pollution levels that would have occurred without the Games, along with a review of policy documents detailing event-specific environmental measures. The findings indicate that air quality significantly improved from March to December 2021, with positive effects lasting up to eight months after the Olympics. These improvements resulted from a combination of targeted emission controls, transition to cleaner energy sources, and strict enforcement measures. The findings indicate that well-designed and consistently enforced environmental policies implemented during mega-events can produce lasting benefits for urban air quality. This study offers valuable insights for policymakers and event organizers aiming to use global sporting events to promote sustainable urban management.

1. Introduction

Mega-sporting events (MSEs) like the Olympic Games have profound and complex effects on host cities, shaping not only economic and social dynamics (Müller and Gaffney, 2018; Scandizzo and Pierleoni, 2018) but also their environmental trajectories (Jin et al., 2011). Over the past three decades, environmental sustainability has become an essential dimension of event planning and evaluation. Among the various sustainability concerns, air quality stands out as both a public health priority and a visible indicator of environmental management performance (Paquette et al., 2011). Deteriorating air quality can undermine athletes' performance, harm residents' health (Huang et al., 2018; Kansal et al., 2009), and tarnish a city's global image as a host destination. Consequently, ensuring clean air has become a defining test of urban governance during MSEs.

Empirical evidence from previous Olympic Games and other MSEss reveals a recurring pattern: short-term environmental gains achieved through intensive, temporary control measures that rarely persist after the closing ceremony. For instance, the 2008 Beijing Olympics produced notable reductions in sulfur dioxide and particulate matter due to factory closures and traffic restrictions, yet pollution levels rebounded shortly thereafter (Chen et al., 2013). A systematic review of 171 studies between 2000 and 2021 found that negative environmental effects of mega-events (62%) still outweighed positive ones (33%), underscoring the persistent challenge of achieving sustainable outcomes (Cerezo-Esteve et al., 2022). The scholarly debate, therefore, centers on whether these events can move beyond symbolic "green games" rhetoric to deliver enduring ecological benefits.

MSEs can, however, open unique policy windows that enable governments to enact otherwise difficult environmental reforms (Milton and Grix, 2015). Heightened international scrutiny, media attention, and political commitment can temporarily align incentives for inter-agency cooperation and stricter regulation. If strategically leveraged, this convergence of pressures can transform short-term compliance into longer-term institutional change (Death, 2011; Mol and Sonnenfeld, 2000). The key question is what conditions cause these

* Corresponding author.
E-mail address: markus.lang@unil.ch (M. Lang).

https://doi.org/10.1016/j.clpl.2025.100116
Received 1 July 2025; Received in revised form 28 October 2025; Accepted 11 November 2025
Available online 18 November 2025

temporary governance efforts to result in long-term improvements in environmental quality. Understanding these mechanisms is especially important for rapidly growing urban areas where air pollution remains severe and administrative enforcement capacity varies.

Beijing offers an outstanding example for examining this issue. Once associated with smog and heavy coal reliance, the city has, since 2013, introduced a series of aggressive air pollution control measures, including energy shifts, industrial restructuring, and regional coordination with neighboring provinces (Zhang et al., 2016). The preparation for the 2022 Winter Olympics was not just an environmental campaign for a specific event but the result of nearly a decade of policy testing. Unlike the 2008 Olympic Games, which depended on temporary shutdowns, the 2022 Games were part of China's broader "Blue Sky" and carbon-neutrality. The Games' official vision—"green, inclusive, open and clean"—clearly presents sustainability as a key legacy goal (Beijing Organising Committee for the 2022 Olympic and Paralympic Winter Games, 2022). Therefore, the event provides a valuable chance to evaluate whether ongoing governance reforms can lead to measurable, lasting improvements in air quality.

The present study explores whether the 2022 Beijing Winter Olympics led to lasting improvements in urban air quality and what policy mechanisms supported these changes. While prior research has documented temporary drops in pollutants during mega-events, few studies have used counterfactual modeling to assess whether these improvements persisted after the event. Additionally, most existing analyses focus on individual pollutants—typically $PM_{2.5}$ or NO_2—without considering the cumulative exposure residents experience (Dominici et al., 2010). To address these gaps, this study employs an event-study methodology using monthly Air Quality Index (AQI) data, enabling a comprehensive assessment of overall air quality trends. The quantitative analysis is supplemented by a review of key policy documents to provide context for the observed changes and to identify governance features that have contributed to sustained improvements.

By combining statistical modeling with policy analysis, this research contributes to three interconnected areas. First, it enhances empirical understanding of the environmental impacts of MSEs by measuring not only immediate but also medium-term effects on air quality. Second, it enriches theoretical debates on the governance of sustainability transitions, showing how a mega-event can serve as a controlled, time-limited policy experiment within broader urban environmental strategies. Third, it offers practical insights for policymakers in other developing or rapidly urbanizing regions, demonstrating how mega-events can act as catalysts for structural reforms in energy use, transportation management, and regional cooperation.

Ultimately, analyzing Beijing's experience helps answer whether mega-events can evolve from short-term displays of "green performance" into true catalysts for sustainable urban change. The Beijing 2022 case provides a rare chance to test this idea empirically, illustrating how ongoing governance and policy integration can turn quick fixes into lasting environmental legacies.

2. Literature review

2.1. MSEs and air pollution

Recent research has increasingly explored the relationship between MSEs and the air quality of host cities (Boykoff and Mascarenhas, 2016; Chen et al., 2013; B. Li et al., 2019; Y. Li et al., 2011; Streets et al., 2007). However, there is still no clear consensus regarding their broader environmental consequences. A systematic review by Cerezo-Esteve et al. (2022) of studies published between 2000 and 2021 revealed that only 32.9% of reported effects were positive, while 62.0% were negative and 5.1% remained inconclusive. For instance, during the "Olympic Days" of Torino (2006), mean $PM_{2.5}$ concentrations in January–February 2006 exceeded those recorded during the same period in 2005 (Traversi et al., 2008). Similarly, Watanabe et al. (2023) found that increases in attendance at National Football League games were associated with higher local ozone and nitrogen dioxide levels, suggesting that crowd-related vehicular traffic can temporarily worsen air quality around large events.

By contrast, other studies report positive environmental outcomes when stringent policy interventions accompany event organization. For example, Li et al. (2021) showed that mega-events featuring short-term air pollution controls—such as international conferences—achieved an average 44% reduction in ambient $PM_{2.5}$ concentrations. Temporary governmental measures, including traffic restrictions and industrial shutdowns, can effectively reduce pollution and even help overcome initial resistance from industry and citizens (Li et al., 2019). The 2008 Beijing Olympics represent a prominent example: vehicle bans and factory closures implemented ahead of the Games substantially lowered $PM_{2.5}$ levels (Wang et al., 2010), while the Rio 2016 Olympics also yielded short-term improvements across several pollutants (De La Cruz et al., 2019; Scandizzo and Pierleoni, 2018). These cases underscore the important role of policy design, early-stage planning, and administrative enforcement in mitigating event-related pollution.

Nevertheless, most existing analyses remain confined to pre- and mid-event periods, leaving the post-event legacy insufficiently examined and raising uncertainty about the persistence of environmental benefits (Liu et al., 2016; Ma et al., 2020). Pollution levels may rebound once temporary controls are lifted. More systematic assessment of policy continuity and governance integration after the event is thus essential to determine whether improvements are sustained or merely cyclical.

Recent debates in the literature reflect a broader shift from "impact" to "leverage" perspectives in the study of mega-events (O'Brien and Chalip, 2008; Schulenkorf et al., 2024). Instead of treating such events as isolated disruptions, the event leveraging framework conceptualizes them as strategic opportunities for achieving lasting urban and environmental benefits that do not occur automatically through event staging alone. Within this approach, sustainability is embedded in planning and governance from the outset, enabling host cities to align event preparation with long-term environmental policy goals (Smith, 2014). Empirical evidence from the past decade increasingly supports this view, emphasizing that multi-level governance coordination, long-term policy integration, and adaptive management are key determinants of whether environmental legacies endure beyond the closing ceremony (Jiang et al., 2024; Shen and Ahlers, 2019).

Accordingly, a systematic examination of policy documents across pre-, mid-, and post-event stages is critical to understanding how governments design and implement air quality interventions as part of broader environmental governance systems. Such an approach not only clarifies the mechanisms through which mega-events influence air pollution but also contributes to emerging discussions on how temporary policy windows can be leveraged to promote continuous urban sustainability and institutional learning.

2.2. Sources of air pollution and MSEs

Air pollution in urban areas originates primarily from stationary and mobile sources. Stationary sources include industrial production, residential heating, and power generation, while mobile sources consist mainly of vehicles, buses, and aircraft. As effective regulatory controls have led to notable declines in sulfur dioxide emissions over recent decades, scholarly and policy attention has increasingly shifted toward secondary pollutants such as ozone (O_3), nitrogen dioxide (NO_2), and fine particulate matter ($PM_{2.5}$ and PM_{10}) (Brunekreef and Holgate, 2002). The main driver of anthropogenic NO_x emissions remains fossil-fuel combustion, produced by both stationary and transport-related activities.

Particulate pollution, especially $PM_{2.5}$, is now recognized as one of the most critical threats to public health and environmental quality. It typically arises from seven major sources: dust resuspension, fossil-fuel combustion, vehicle exhaust, waste incineration, biomass burning, industrial processes, and the formation of secondary inorganic aerosols (B. Li et al., 2019; Zhu et al., 2018). These sources interact dynamically, amplifying local and regional air quality challenges, particularly in megacities with high population density and intensive mobility demands.

During MSEs, mobile sources become particularly influential. Large volumes of spectator and service-vehicle traffic increase NO_x and particulate emissions, while temporary energy demand from event facilities, lighting, and accommodation contributes additional CO_2 and ozone precursors. Preparatory infrastructure projects—such as venue construction and urban redevelopment—also generate considerable dust and construction-related emissions that can temporarily offset environmental gains. The cumulative result is often a dual pressure: short-term emissions surges preceding and during the event, followed by intensive mitigation measures aimed at achieving acceptable air quality standards during the competition period.

Recent research emphasizes that focusing on a single pollutant, such as $PM_{2.5}$, provides only a partial view of environmental outcomes. Integrated, multi-pollutant assessments—capturing the interplay among particulate matter, ozone, nitrogen oxides, and volatile organic compounds—offer a more accurate and policy-relevant understanding of event-related impacts (Dominici et al., 2010). Such holistic analyses can help disentangle the overlapping influences of energy consumption, transportation intensity, meteorological variation, and temporary policy interventions.

In this context, evaluating the environmental footprint of MSEs requires moving beyond single-indicator approaches toward system-level assessments that reflect the complexity of urban atmospheric processes. Understanding how event-specific emission patterns interact with existing pollution sources is crucial not only for quantifying short-term impacts but also for informing the design of long-term, adaptive urban air-quality governance strategies.

2.3. The dual impact of MSEs on environmental policy and sustainability

The interaction between mega-events and environmental sustainability is best understood through the dual lenses of event studies and urban governance. Mega-events frequently function as temporary "policy windows" (Milton and Grix, 2015), enabling authorities to introduce environmental measures that might otherwise encounter political, economic, or social resistance. The intense global visibility and political pressure surrounding such events create favorable conditions for governments to enact stricter environmental regulations and strengthen enforcement mechanisms. Historical examples—including the 1994 Lillehammer Winter Olympics (Essex and Chalkley, 2004), the 2000 Sydney Olympics (Briese, 2001), and the 2008 Beijing Olympics (Mol, 2010)—illustrate how host cities have sought to stage "green games," using them as platforms for broader strategies of ecological modernization (Death, 2011; Mol and Sonnenfeld, 2000).

Yet, translating these short-term environmental gains into enduring outcomes remains a central challenge. The existing literature reveals a clear division of perspectives. One line of research views mega-events as catalysts for long-term transformation, stimulating investments in clean technologies, renewable energy, and improved environmental governance frameworks (Death, 2011; Milton and Grix, 2015). Others argue that such effects are often ephemeral, noting that environmental measures tend to be relaxed once the event concludes, leading to a rapid rebound in pollution levels (Liu et al., 2016). Temporary shutdowns of industrial plants, short-term traffic bans, or intensified enforcement during competition periods frequently yield visible but unsustainable improvements that dissipate without institutional continuity.

A critical distinction of the Olympic Games relative to other mega-events lies in their extended preparation horizon and phased governance structure. For instance, the U.S. Olympic bidding process—initiated years before host selection—illustrates how Olympic planning unfolds over roughly a decade, allowing for cumulative implementation of environmental regulations and infrastructure upgrades (Kassens-Noor and Lauermann, 2017). This prolonged timeline transforms the Games into a natural experiment for observing how environmental governance evolves through successive stages of policy design, enforcement, and legacy management.

Accordingly, assessing the environmental implications of mega-events requires a comprehensive, longitudinal framework that examines pre-event preparations, event-time interventions, and post-event governance. Methodologically, event-study analysis (Dick and Wang, 2010) and counterfactual simulation techniques (S. Li et al., 2021) provide valuable tools for segmenting and quantifying these temporal effects. Such an integrated approach allows researchers to disentangle transient impacts from structural change, thereby clarifying how mega-events can contribute to sustainable urban transformation when embedded within consistent, long-term policy systems.

3. The 2022 Beijing Winter Olympic Games

3.1. Key policy documents and management measures

The Chinese government viewed the 2022 Beijing Winter Olympics as a strategic opportunity to demonstrate its environmental commitment and strengthen sustainable urban governance. In preparation for the Games, a comprehensive air quality management framework was implemented, emphasizing a transition from coal to cleaner energy sources such as natural gas, large-scale promotion of electric vehicles, and the enforcement of stricter industrial emission standards. These efforts reflected a multiphased and integrated approach designed not only to ensure "blue skies" during the Games but also to establish a long-term foundation for sustainable air quality improvements.

Beijing's Olympic air quality management strategy unfolded across three interconnected phases, each addressing specific environmental challenges through targeted policy interventions. Together, these phases embodied an advanced model of event-driven environmental governance, combining long-term planning, iterative policy enhancement, and emergency response mechanisms. The key stages are summarized below.

3.1.1. 2013–2020: Long-term planning and foundation building

During this initial stage, Beijing established the institutional and regulatory foundations for improved air quality. Two cornerstone policies—the *Five-Year Clean Air Action Plan (2013–2017)* and *Beijing's Three-Year Action Plan for Winning the Blue Sky Battle (2018–2020)*—set ambitious objectives to reduce $PM_{2.5}$ concentrations and overall pollution intensity. Measures focused on controlling emissions from major pollution sources, optimizing the energy mix, and tightening enforcement of emission standards. These actions laid the groundwork for a cleaner urban environment and positioned the city to meet the stringent requirements of hosting the Winter Olympics.

3.1.2. Pre-Event Phase (2021): Consolidation and targeted management

Building on the progress achieved in the previous decade, Beijing launched the *Air Pollution Prevention and Control Action Plan (2021)* to further consolidate environmental gains and prepare for the Games. The plan introduced integrated control of $PM_{2.5}$ and ozone (O_3), focusing on the joint reduction of volatile organic compounds (VOCs) and nitrogen oxides (NO_x). It promoted the application of ultra-low emission technologies in key industries, the expansion of new-energy vehicles, and strengthened dust and construction site emission controls. These measures reflected a transition from broad-based pollution reduction to more refined, data-driven management.

3.1.3. Event Period (February–March 2022): Temporary emergency and traffic control measures

During the Olympic and Paralympic Games, Beijing implemented temporary but highly coordinated emergency controls to maintain

Table 1
Air pollution prevention policies implemented during the 2022 Beijing Winter Olympics.

Title	Release Date	Main Content
Five-Year Clean Air Action Plan (2013–2017)[a]	Sep-2013	**Objective:** To significantly improve air quality over five years and markedly reduce heavy pollution days. By 2017, the annual average concentration of $PM_{2.5}$ should be reduced by over 25 % compared to 2012, aiming to stabilize around 60 μg/m^3. **Measures:** a. Eight Major Pollution Reduction Projects (source control, energy structure adjustment, vehicle structure adjustment, industrial structure optimization, end-of-pipe pollution control, urban exemplary management, ecological environment construction, emergency reduction measures for severe air pollution) b. Six Implementation Assurance Measures (improving the regulatory framework, innovating economic policies, strengthening technological support, enhancing organizational leadership, decomposing responsibilities, and strict assessment and accountability) c. Three Public Participation Actions (enterprise self-discipline for pollution control, public voluntary pollution reduction, and social supervision for pollution prevention).
Beijing's Three-Year Action Plan for Winning the Blue Sky Battle (2018–2020)[b]	Sep-2018	**Objective:** By 2020, further improve air quality from the "13th Five-Year Plan" targets, with a significant reduction in $PM_{2.5}$ concentration, a notable decrease in heavy pollution days, and enhanced public satisfaction with blue skies. Reduce the total emissions of major air pollutants substantially, and jointly reduce greenhouse gas emissions, aiming for a reduction of over 30 % in nitrogen oxides and volatile organic compounds compared to 2015; reduce the ratio of heavy pollution days by more than 25 % compared to 2015. **Measures:** a. Adjust the transportation structure, promote vehicle electrification, accelerate the elimination of old vehicles, and reduce vehicle usage intensity b. Improve the dust control responsibility system, focusing on construction site dust, road dust, and exposed surface dust, and enhance urban exemplary management c. Optimize and adjust the industrial structure, develop energy-saving and environmental protection industries, and promote profound industrial pollution control d. Optimize and adjust the energy structure, fully develop local renewable energy resources, and accelerate the construction of clean energy infrastructure e. Strengthen pollution control in the domestic sector, with a focus on industries such as building decoration, catering, and auto repair, develop agricultural circular economy, and improve agricultural production structures in line with environmental carrying capacity f. Focus on pollution control in autumn and winter and enhance responses to severe air pollution.
Air Pollution Prevention and Control Action Plan (2021)[c]	Mar-2021	**Objective:** Consolidate improvements in air quality and strive for a continued decrease in heavy pollution days. **Measures:** a. Implement volatile organic compounds (VOCs) control measures, including using big data technologies for management and strengthening oversight in construction projects b. Optimize the vehicle structure by promoting new energy vehicles and enhancing regulatory measures c. Advance clean and low-carbon energy by upgrading existing heating systems, researching energy-saving technologies for buildings, and promoting the use of renewable energy sources (e.g., photovoltaic systems, local heat pumps); d. Refine dust management, focusing on roads, construction sites, and agricultural lands e. Collaborate with surrounding regions to advance coordinated air pollution control
Notice by the Beijing Municipal Government on Temporary Traffic Management Measures during the 2022 Winter Olympics and Paralympics[d]	Jan-2022	**Objective:** Ensure smooth and safe traffic during the 2022 Winter Olympics and Paralympics and minimize the impact of traffic on the events. **Measures:** a. Motor vehicles must comply with the Olympic designated lane regulations b. Implement vehicle restrictions on specific dates c. Prohibit the passage of hazardous chemical vehicles, which must be registered d. Restrict construction waste transportation e. Restrict vehicle operations during periods of air pollution
Air Pollution Prevention and Control Action Plan (2022)[e]	Mar-2022	**Objective:** Maximize the consolidation of improvements in air quality. **Measures:** a. Implement targeted actions for nitrogen oxide reduction b. Execute special measures for the control of volatile organic compounds (VOCs) c. Enhance urban environmental exemplary management d. Advance regional air pollution joint prevention and control

[a] See https://sthjj.beijing.gov.cn/bjhrb/index/xxgk69/sthjlyzwg/wrygl/603133/index.html.
[b] See https://www.beijing.gov.cn/zhengce/zhengcefagui/201905/t20190522_61552.html.
[c] See https://www.beijing.gov.cn/zhengce/zcjd/202103/t20210304_2298429.html.
[d] See https://www.beijing.gov.cn/zhengce/zfwj/zfwj2016/szfwj/202201/t20220114_2590998.html.
[e] See https://www.beijing.gov.cn/zhengce/zhengcefagui/202203/W020220302396511200452.pdf.

optimal air quality and traffic conditions. The *Notice by the Beijing Municipal Government on Temporary Traffic Management Measures during the 2022 Winter Olympics and Paralympics* outlined actions such as Olympic-exclusive traffic lanes, alternating license plate restrictions, the diversion of heavy-duty freight trucks, and the prohibition of vehicles carrying hazardous materials. Construction-related transportation was temporarily suspended, and additional restrictions were activated during severe pollution alerts. These measures effectively minimized emissions from vehicular and construction activities during the Games.

3.1.4. Post-Event Phase (2022): Sustaining gains and expanding policy scope

Following the Games, Beijing continued its proactive environmental governance through the *Air Pollution Prevention and Control Action Plan (2022)*. This plan reinforced the dual-control strategy for $PM_{2.5}$ and ozone, advanced the deployment of ultra-low emission technologies, and intensified efforts to curb VOC and NO_x emissions. It also emphasized the further optimization of transport and industrial structures, the expansion of new energy vehicle fleets, and the comprehensive management of construction dust. These continued measures aimed to consolidate achievements from the Olympic period, prevent post-event pollution rebounds, and institutionalize best practices into the city's long-term sustainability framework.

Collectively, these sequential plans demonstrate the evolution of Beijing's environmental governance from short-term, reactive interventions toward a systematic, technology-supported, and regionally coordinated model of air quality management. Table 1 provides an overview of the major air pollution prevention policies implemented across the Olympic cycle.

3.2. Comparison of air quality management policies for the 2008 Beijing Summer Olympics and the 2022 Beijing Winter Olympics

The air quality management policies implemented for the 2008 Beijing Summer Olympics and the 2022 Beijing Winter Olympics, while both targeting improved air quality, differed significantly in focus, approach, and context. During the 2008 Summer Olympics, Beijing was experiencing rapid industrialization and urbanization, with air pollution primarily driven by PM_{10} and nitrogen oxide emissions. To address these issues, Beijing had already launched a series of long-term air quality initiatives, including coal-consumption reduction, energy-structure adjustment, and the gradual tightening of vehicle emission standards. Building on this foundation, air quality management strategies at the time relied heavily on short-term emergency measures, including temporary closures of high-pollution industries, vehicle license plate restrictions, and suspensions of construction activity. These interventions were primarily administrative, targeting pollution sources through direct regulatory actions designed to yield immediate improvements in air quality.

In contrast, the policies for the 2022 Winter Olympics were developed within a broader framework of ongoing air quality improvements achieved over the preceding decade. This time, the focus shifted to long-term control of pollutants like $PM_{2.5}$ and ozone, with an increased emphasis on managing volatile organic compounds (VOCs). The 2022 policies increasingly incorporated technology-driven strategies, including real-time monitoring systems and regional collaborative governance, mainly through coordinated efforts among the Beijing-Tianjin-Hebei region. These measures promoted cleaner energy sources and low-carbon development.

Furthermore, the 2022 policies were aligned with the goals of carbon neutrality and sustainable development, encouraging widespread adoption of renewable energy and low-emission transportation to meet green Olympic standards. Overall, Beijing's approach to pollution control evolved from the short-term emergency interventions of 2008 to a systematic, long-term strategy by 2022. This evolution involved structural upgrades in industry and energy, regional collaboration, and technological innovation, along with a focus on carbon neutrality, illustrating a more comprehensive and sustainable environmental management approach.

4. Data and methods

4.1. Methodology

This study employs the event study methodology to evaluate the impact of the 2022 Beijing Winter Olympics on urban air quality. The event study approach was initially developed in financial economics to assess the abnormal returns associated with specific market events (Armitage, 1995; MacKinlay, 1997). It has since been widely adopted in other fields—such as marketing, environmental economics, and policy evaluation—to examine how discrete interventions influence measurable outcomes (B. Li et al., 2019; Ma et al., 2020; Sorescu et al., 2017). The method provides a quasi-experimental framework that isolates the causal effect of a defined event by comparing observed data with a modelled "counterfactual" scenario that estimates what would have occurred in the event's absence. Its flexibility and causal interpretability make it particularly suitable for assessing the environmental outcomes of policy-driven events such as the Olympic Games, where interventions are concentrated within clearly defined temporal windows.

Following standard practice, the event study design in this paper comprises five main steps (Li et al., 2019):

1. **Defining the event window:** establishing the period before, during, and after the event to capture any measurable changes in the outcome variable.
2. **Collecting actual data:** compiling monthly AQI levels and relevant control variables to represent observed outcomes.
3. **Estimating a regression model:** using historical data from the estimation window to construct a baseline model that reflects typical air quality dynamics.
4. **Estimating the counterfactual:** projecting expected AQI levels as if the Winter Olympics had not occurred.
5. **Comparing actual versus counterfactual trends:** evaluating deviations between observed and predicted values to quantify the direct effect of the event.

Consistent with previous applications of event studies to environmental data (B. Li et al., 2019; Ma et al., 2020), this study defines four distinct observation windows: (1) an estimation window (January 2014–October 2020) to establish baseline trends; (2) a pre-event treatment window (March 2021–January 2022) capturing intensified environmental measures before the Games; (3) an event window (February–March 2022) corresponding to the Olympic period; and (4) a post-event window (April–November 2022) assessing whether improvements were sustained after the withdrawal of Olympic-related interventions.

4.2. Data

The selection of variables in our regression model is grounded in the understanding that air quality is determined by both socioeconomic and environmental factors (Zhan et al., 2018). Prior studies show that pollution levels are influenced by industrial activity (Ehrlich et al., 2007), vehicle emissions (Fang et al., 2016), and dust from construction projects (Yan et al., 2019). In China, the main contributors to $PM_{2.5}$ pollution are coal combustion, motor vehicle emissions, and industrial processes (Pui et al., 2014). These findings informed the inclusion of variables that jointly capture economic activity, transportation, and environmental conditions in our model, ensuring a comprehensive assessment of the determinants of air quality.

In recent years, Beijing has pursued an ambitious clean energy strategy that reduced coal consumption in industrial and residential sectors and expanded electricity- and gas-based energy systems. Consequently, coal combustion has ceased to be a dominant pollution source. Heavy-duty diesel trucks, however, remain a major factor influencing aerosol formation (Rogge et al., 1993). Because Beijing's air pollution control policies have targeted diesel vehicle emissions through stringent regulations and enforcement actions, Diesel Output was incorporated as a key explanatory variable.

Natural conditions also play a decisive role in shaping air quality. Temperature and humidity affect atmospheric dispersion and chemical reactions, while wind speed may exert variable effects depending on seasonal conditions. To account for these influences, meteorological variables—average temperature and humidity—were included as controls.

The dependent variable, the Air Quality Index (AQI), is a composite indicator based on the concentrations of six pollutants: sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), ozone (O_3), and particulate matter (PM_{10} and $PM_{2.5}$). These pollutants are continuously monitored through a network of urban air quality stations, providing a comprehensive measure of overall atmospheric conditions.

Data on AQI and humidity were obtained from the *AQI-Study* monitoring platform (https://www.aqistudy.cn/historydata/). Socioeconomic indicators—including industrial output, fixed asset investment, diesel production, and highway passenger volume—were retrieved from the *Beijing Statistical Bureau* (https://tjj.beijing.gov.cn/) and *China Economic Net* (https://db.cei.cn/jsps/Home). Monthly average temperature data were sourced from the *China Meteorological Center* and the *Dalian Commodity Exchange*, which jointly compile the *Central Meteorological Observatory – DCE Temperature Index* (http://index.nmc.cn/).

The study covers the period January 2014 to November 2022, encompassing the years preceding, during, and following the 2022 Beijing Winter Olympics. This time span enables an examination of both the preparatory and legacy effects of Olympic-related environmental policies.

Table 2 presents the variable definitions and descriptive statistics used in the analysis.

4.3. Regression model

To estimate the counterfactual scenario—what Beijing's air quality would likely have been in the absence of the Winter Olympics—we developed a multiple linear regression model based on historical and contemporaneous socioeconomic and meteorological data. This model captures normal fluctuations in air quality and isolates the specific effect of Olympic-related interventions.

The monthly average AQI serves as the dependent variable, reflecting overall air pollution levels. Independent variables include indicators of industrial and investment activity, transportation intensity, and meteorological conditions. Specifically, the model incorporates:

- IND – year-on-year growth rate of industrial added value, representing production activity;
- INV – cumulative year-on-year growth rate of fixed-asset investment, capturing construction and infrastructure expansion;
- DO – diesel output, serving as a proxy for freight transport and energy-related emissions;
- PV – highway passenger volume, indicating mobility and vehicle traffic intensity;
- MAT – monthly average temperature;
- MAH – monthly average humidity.

To control for cyclical variations in weather, traffic, and industrial activity, quarterly fixed effects were introduced. The resulting model can be expressed as follows:

$$AQI_t = \beta_0 + \beta_1{*}IND + \beta_2{*}INV + \beta_3{*}DO + \beta_4{*}PV + \beta_5{*}MAT + \beta_6{*}MAH + \text{Quarterly fixed effects} + \varepsilon_t \quad (1)$$

where ε_t denotes the error term.

The model was estimated using Ordinary Least Squares (OLS) over the estimation window (January 2014–October 2020)—the period preceding the introduction of Olympic-related environmental measures. This baseline captures normal economic and meteorological dynamics in the absence of the event. The estimated coefficients were then applied to the event and post-event periods to generate counterfactual AQI values, representing expected pollution levels without the Winter Olympics interventions.

Comparing these predicted counterfactuals with the observed AQI during and after the Games enables us to quantify the direct and residual effects of the Olympic environmental policies. This regression-based counterfactual design provides a transparent, data-driven means to distinguish the Olympic impact from underlying structural and seasonal trends.

5. Results

5.1. Regression model

Table 3 presents the results of the OLS regression estimating the determinants of Beijing's monthly Air Quality Index (AQI) during the baseline period (January 2014–October 2020). The model explains approximately 44.8% of the variation in AQI values ($R^2 = 0.448$), and the F-statistic (7.24, $p < 0.001$) confirms its overall significance.

The results indicate that both diesel output and highway passenger volume have statistically significant positive effects on AQI levels ($p < 0.05$), suggesting that emissions from heavy-duty vehicles and passenger transport are major contributors to urban air pollution. Monthly average humidity also shows a strong positive relationship with AQI ($p < 0.01$), indicating that higher humidity levels may promote the accumulation of fine particulates in the atmosphere.

The growth rate of fixed-asset investment exerts a marginally significant positive influence ($p < 0.10$), implying that intensified construction activity and industrial expansion tend to increase pollution. In contrast, industrial added value growth and average temperature display negative but statistically insignificant coefficients, suggesting limited direct influence on monthly air quality within the baseline window.

Quarterly fixed effects account for seasonal variations associated with weather conditions, heating periods, and construction cycles.

Table 2
Definitions of variables and descriptive statistics.

Variable	Description	Unit	Obs	Mean	Std. dev.	Min	Max
AQI	Air Quality Index (AQI)	Index Value	126	94.21	27.76	47	187
IND	Current year-on-year growth rate of industrial-added value	%	112	4.73	14.48	−39.6	67.5
INV	Cumulative year-on-year growth rate of Investment in fixed assets	%	115	5.43	7.09	−19.9	29.8
DO	Diesel Output	10,000 Metric Tons	106	15.07	3.48	4.1	24.73
PV	Highway Passenger Volume	Million Person-times	124	32.10	10.29	7.46	47.35
MAT	Monthly Average Temperature	Index Value	126	113.71	10.85	95.82	128.95
MAH	Monthly Average Humidity	Index Value	126	50.75	12.35	29	78

Table 3
Results of the regression analysis for predicting the air quality index(baseline period, January 2014-October 2020).

Variable	AQI
Current year-on-year growth rate of industrial-added value (IND)	0.0554 (0.497)
Cumulative year-on-year growth rate of investment in fixed assets (INV)	0.661* (0.351)
Diesel Output (DO)	1.929** (0.788)
Highway Passenger Volume (PV)	0.685** (0.297)
Monthly Average Temperature (MAT)	−0.677 (0.951)
Monthly Average Humidity (MAH)	1.528*** (0.416)
Constant	68.32 (95.60)
Quarterly Dummies	Yes
R-squared	0.448
Observations	68

Note: Coefficients were estimated using OLS regression. Due to incomplete data for January, all data related to January have been excluded from this regression analysis. Robust standard errors are in parentheses. The dependent variable is AQI. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

Overall, the regression results emphasize that transportation and fuel-related factors—particularly diesel use and traffic intensity—remain key drivers of pollution in Beijing, despite substantial progress in energy restructuring and industrial upgrading.

These coefficient estimates provide the foundation for constructing the counterfactual model, which projects expected AQI levels in the absence of Olympic-related interventions. The resulting comparison between observed and counterfactual values allows for the quantification of both short-term and sustained environmental effects associated with the 2022 Beijing Winter Olympics.

5.2. Counterfactual scenario and comparison with the actual AQI

Using the estimated coefficients from the baseline regression, we constructed a forecasting model to generate counterfactual AQI values—representing expected air quality levels in the absence of Olympic-related interventions. The specification can be expressed as:

$$AQI_t = 68.32 + 0.0554*IND + 0.661*INV + 1.929*DO + 0.685*PV - 0.677*MAT + 1.528*MAH + \text{Quarterly fixed effects} + \varepsilon_t \quad (2)$$

By comparing these counterfactual projections with the observed AQI values during and after the 2022 Winter Olympics, we can isolate the incremental impact of Olympic-related policies and management measures on air quality.

As shown in Table 4 and Fig. 1, Beijing experienced a marked and sustained reduction in pollution levels beginning in the months preceding the Games. From April to December 2021, observed AQI values were consistently lower than their counterfactual estimates, particularly in October, November and December, suggesting that pre-Olympic environmental measures—such as stricter emissions standards, the promotion of new-energy vehicles, and enhanced construction-site dust control—were already yielding measurable benefits.

During the event window (February–March 2022), the observed AQI reached its lowest recorded levels (47 in February), significantly below the counterfactual projection. This period coincided with temporary but comprehensive traffic and industrial restrictions implemented through the *Notice by the Beijing Municipal Government on Temporary Traffic Management Measures during the 2022 Winter Olympics and Paralympics*, underscoring the effectiveness of targeted short-term interventions in curbing vehicular and industrial emissions.

Importantly, these improvements persisted beyond the event itself. From March to November 2022, actual AQI levels remained below the projected counterfactuals for most months, indicating that Beijing successfully avoided the typical post-event rebound effect observed in earlier mega-events. The sustained improvement reflects the continuation of the *Air Pollution Prevention and Control Action Plan (2022)*, which extended many Olympic-era measures, reinforced industrial emission controls, and further expanded clean-energy use.

Table 4
Comparison of actual and counterfactual air quality index (AQI) levels before, during and after the 2022 Beijing Winter Olympics (March 2021–December 2022).

Month/Year	Actual AQI	Counterfactual AQI	Difference
Mar-21	149	130	19
Apr-21	71	83	−12
May-21	84	91	−7
Jun-21	85	106	−21
Jul-21	71	104	−33
Aug-21	72	93	−21
Sep-21	57	106	−49
Oct-21	50	100	−50
Nov-21	75	101	−26
Dec-21	55	88	−33
Jan-22	68	–	–
Feb-22	47	–	–
Mar-22	70	123	−53
Apr-22	74	92	−18
May-22	86	85	1
Jun-22	102	111	−9
Jul-22	86	94	−8
Aug-22	67	89	−22
Sep-22	91	75	16
Oct-22	65	87	−22
Nov-22	71	91	−20

Note: Due to the lack of diesel output data, the forecast calculations for January 2022 and February 2022 were not performed.

Overall, the comparison between actual and counterfactual AQI trajectories demonstrates that the 2022 Beijing Winter Olympics generated significant and lasting air-quality benefits, achieved through a combination of long-term governance reforms and short-term regulatory intensification. These findings highlight how mega-events, when embedded within sustained environmental policy frameworks, can serve as catalysts for enduring urban air-quality improvements.

5.3. Evolution of key pollutants over time

To complement the AQI-based analysis, this section examines the temporal evolution of the six atmospheric pollutants constituting the AQI—$PM_{2.5}$, PM_{10}, NO_2, CO, O_3, and SO_2—from March 2021 to November 2022. Fig. 2 illustrates these pollutant trends in relation to the key government interventions outlined in Section 3, enabling a clearer understanding of how different policy phases affected emission patterns.

During the pre-event period (March 2021–January 2022), average concentrations of $PM_{2.5}$ and PM_{10} were maintained at relatively low levels (29.36 μg/m^3 and 48.45 μg/m^3, respectively), while mean NO_2 and CO concentrations were 26.18 μg/m^3 and 0.58 μg/m^3. These results coincide with the implementation of the *Air Pollution Prevention and Control Action Plan (2021)*, which strengthened controls on volatile organic compounds (VOCs) and nitrogen oxides, promoted ultra-low-emission technologies, optimized the vehicle fleet, and tightened construction-dust regulations. The steady decline in particulate and nitrogen-oxide levels during this phase demonstrates the effectiveness of these structural interventions.

In the event period (February–March 2022), further reductions were recorded across nearly all pollutants, with the lowest $PM_{2.5}$ and NO_2 values observed in February. These declines correspond to the temporary traffic and industrial restrictions imposed by the *Notice by the Beijing Municipal Government on Temporary Traffic Management Measures during the 2022 Winter Olympics and Paralympics*, including dedicated Olympic lanes, bans on heavy-duty diesel trucks, and strict limits on construction waste transport. The results confirm that short-term regulatory

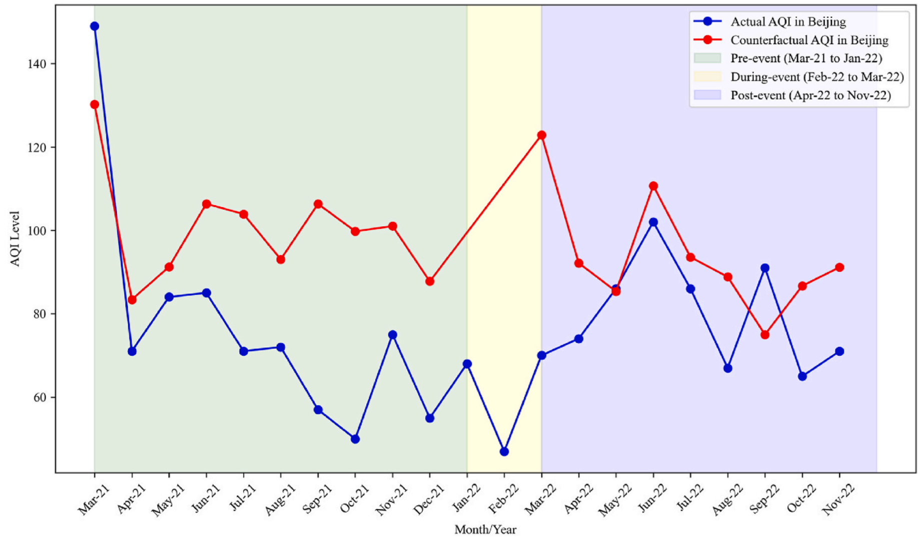

Fig. 1. Comparison of actual and counterfactual air quality index (AQI) levels before, during and after the 2022 Beijing Winter Olympics.

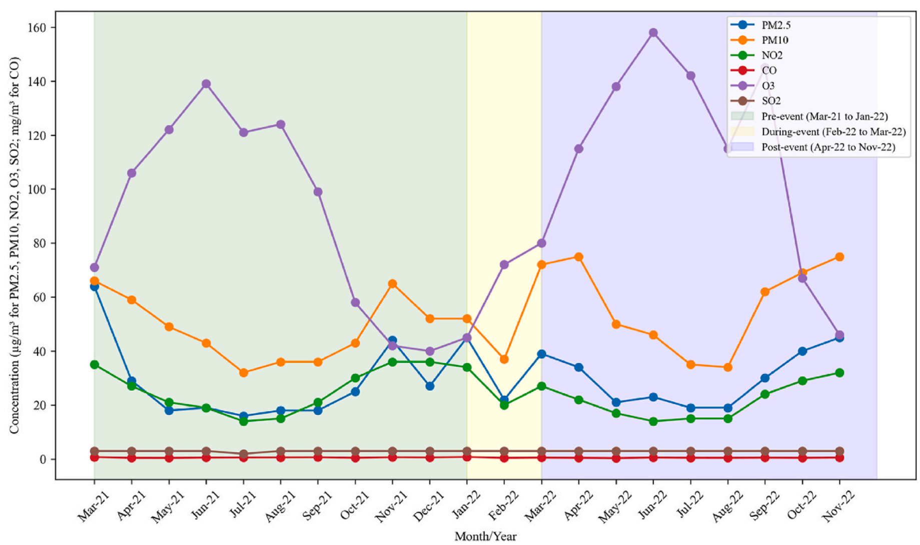

Fig. 2. Temporal trends of key air pollutants observed before, during and after the 2022 Beijing Winter Olympics.

intensification effectively suppressed pollution sources most sensitive to vehicular activity.

In the post-event phase (April–November 2022), concentrations of $PM_{2.5}$, PM_{10}, and NO_2 rose moderately as normal industrial and traffic activity resumed. Nonetheless, levels remained below their 2020–2021 averages, indicating that policy continuity under the *Air Pollution Prevention and Control Action Plan (2022)* mitigated the typical post-event rebound. The increase in ozone (O_3) during the warmer months likely reflects photochemical reactions driven by higher temperatures and sunlight rather than policy relaxation, highlighting the importance of integrating ozone control into future emission-reduction strategies.

Throughout the observation period, SO_2 concentrations remained consistently low (around 3 $\mu g/m^3$), confirming the long-term success of Beijing's energy transition away from coal combustion. The decommissioning of coal-fired power units and the adoption of natural-gas-based heating have effectively eliminated SO_2 as a major pollutant source.

Overall, the pollutant-specific trends validate the counterfactual analysis: sustained declines in $PM_{2.5}$, PM_{10}, and NO_2 during and after the Games indicate that Beijing's Olympic-related governance reforms produced tangible and lasting air-quality gains. These findings underscore that structural energy transitions, combined with short-term event-period measures, can deliver measurable and durable environmental improvements.

6. Discussion

6.1. Overview of findings

The findings of this study offer valuable insights into the effects of mega-sporting events on urban air quality, using the 2022 Beijing Winter Olympics as a representative case. The analysis reveals that Beijing's air quality improved significantly during the event and remained enhanced for several months afterward, demonstrating the effectiveness of the environmental measures implemented. These results align with previous research (e.g., Li et al., 2019; De La Cruz et al., 2019), which finds that intensified pollution controls during large-scale events often lead to short-term air quality gains. However, this study extends existing evidence by documenting a prolonged post-event improvement, suggesting that Beijing's integrated and strategic approach yielded more lasting environmental outcomes.

These findings are broadly consistent with international evidence from cases such as the Rio 2016 Olympics (De La Cruz et al., 2019) and the 2014 APEC Summit in Beijing (Liu et al., 2016), where temporary emission controls improved air quality but effects faded rapidly. In contrast, the 2022 Winter Olympics achieved sustained air-quality gains for several months post-event, underscoring the importance of policy continuity and institutional coordination. Similar to long-term frameworks established after the Sydney 2000 "Green Games" (Briese, 2001) and the Lillehammer 1994 Winter Olympics (Essex and Chalkley, 2004), Beijing embedded its environmental interventions within an evolving governance model rather than relying solely on temporary campaigns. The combination of top-down regulation, technological modernization, and alignment with China's broader carbon-neutrality agenda distinguishes the Beijing case from earlier events driven mainly by short-term environmental targets.

Several factors contributed to the sustained environmental improvements observed during and after the Games. First, the "Olympic effect" itself played a catalytic role. The success of the 2008 Summer Olympics in achieving "Olympic Blue" skies (Brajer and Mead, 2003) set a precedent, prompting the government to adopt long-term air-quality improvement strategies. Early initiatives such as the *Five-Year Clean Air Action Plan (2013–2017)* laid the groundwork for subsequent progress.

Second, policy innovation prior to the 2022 Games was decisive. The *Air Pollution Prevention and Control Action Plan (2021)* targeted key local pollutants such as VOCs, while promoting electric vehicles and clean-energy adoption in line with Beijing's sustainable development agenda.

Third, policy persistence distinguished Beijing's approach from most earlier mega-events. Rather than relaxing regulations once the Games concluded, the government extended and optimized the *2021 Action Plan* through the *2022 Plan*, embedding these measures into the city's ongoing environmental governance framework. This sustained implementation prevented the typical post-event rebound effect and transformed temporary Olympic policies into lasting structural reforms.

6.2. Theoretical implications

From a theoretical perspective, these findings contribute to the literature on event leveraging and ecological modernization (O'Brien and Chalip, 2008; Death, 2011; Mol, 2010; Schulenkorf et al., 2024). The Beijing case exemplifies how mega-events can act as "policy windows" (Milton and Grix, 2015), facilitating the adoption of measures that might otherwise face institutional or political barriers. By combining top-down administrative enforcement with technological modernization, Beijing illustrates how MSEs can serve as long-term governance experiments that extend beyond symbolic environmental commitments. This challenges the notion that MSEs only produce short-term environmental impacts and advances theoretical understanding of how such events can drive systemic, sustainable urban transformation.

6.3. Practical implications

Practically, these results offer transferable lessons for other developing and emerging economies confronting severe air pollution challenges. Cities hosting MSEs—such as New Delhi (Commonwealth Games), São Paulo (World Cup), or Johannesburg (World Cup)—can draw from Beijing's model of continuous monitoring, cross-regional coordination, and incremental electrification of transportation. Embedding event-related environmental measures into ongoing policy frameworks, rather than treating them as isolated campaigns, can enhance both environmental effectiveness and social legitimacy. Moreover, aligning such measures with broader international agendas, including the WHO Air Quality Guidelines (Carvalho, 2021) and the UN Sustainable Development Goals, ensures that mega-events contribute to global sustainability objectives rather than temporary national showcases.

6.4. Limitations and directions for future research

This study has several limitations. Although the models account for the COVID-19 pandemic (2019–2020), isolating its specific effects remains challenging. While the observed improvements are largely attributable to targeted policy interventions, China's stringent lockdown measures between 2020 and 2023 also temporarily reduced emissions from industrial, transport, and energy sectors. The results, therefore, likely reflect a synergistic effect between pandemic-induced reductions and sustained governance. Importantly, the pandemic's influence was short-term, whereas policy-driven measures—such as energy transition, industrial upgrading, and emission-control technologies—represent structural and durable drivers of air-quality improvement.

Future research could apply more sophisticated econometric or spatial models to better disentangle pandemic effects from policy impacts and include higher-resolution activity data to enhance analytical precision. Comparative analyses across multiple Olympic Games would also help determine how different governance models and environmental policies shape the magnitude and persistence of air-quality improvements. Finally, expanding the analytical scope beyond air pollution—considering energy infrastructure, green space development, and greenhouse gas emissions—would yield a more comprehensive understanding of the environmental legacy of MSEs.

7. Conclusions

This study provides robust empirical evidence that MSEs, when embedded within sustained and well-coordinated governance frameworks, can generate enduring improvements in urban air quality. Using an event study methodology to estimate counterfactual air quality in Beijing, the analysis demonstrates that the 2022 Winter Olympics produced significant reductions in pollution that persisted for up to eight months after the event. These results confirm that policy-driven interventions—particularly those institutionalized within long-term urban sustainability plans—are central to achieving measurable and lasting environmental benefits.

The scientific contribution of this research lies in extending the event study methodology to environmental governance, offering a quantitative approach capable of isolating the effects of policy interventions from external shocks. By combining counterfactual modelling with policy document analysis, the study bridges environmental policy evaluation and event legacy research, contributing to a more interdisciplinary understanding of how temporary "policy windows" can be leveraged for sustained ecological improvement.

Practically, the findings provide a transferable model for policymakers and urban planners, particularly in rapidly developing or high-emission contexts. The Beijing case illustrates how mega-events can accelerate transitions toward clean energy, low-emission transport systems, and coordinated regional air quality management. It demonstrates that the "mega-event effect" can move beyond symbolic environmental commitments to deliver tangible, long-term gains when short-term measures are embedded in continuous policy cycles and post-event monitoring.

Future research should further disentangle policy effects from exogenous factors such as pandemics, conduct cross-city comparisons, and examine broader environmental outcomes, including carbon reduction, urban greening, and resource efficiency. Advancing this research agenda will deepen understanding of how mega-events can serve as strategic instruments for sustainable urban transformation.

CRediT authorship contribution statement

Jie Gao: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Markus Lang:** Writing – original draft, Supervision, Investigation, Conceptualization. **Yiyi Jiang:** Writing – original draft, Resources, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

Supported in part by the China Scholarship Council Program.

Data availability

Data will be made available on request.

References

Armitage, S., 1995. Event study methods and evidence on their performance. J. Econ. Surv. 9 (1), 25–52.
Beijing Organising Committee for the 2022 Olympic and Paralympic Winter Games, 2022. Beijing 2022 Pre-games Sustainability Report Outlines Climate Solutions, Development of Winter Sports and Regional Regeneration in China—Olympic News. Olympics.Com. https://olympics.com/ioc/news/beijing-2022-pre-games-sustainability-report-outlines-climate-solutions-development-of-winter-sports-and-regional-regeneration-in-china.
Boykoff, J., Mascarenhas, G., 2016. Rio 2016: urban policies and environmental impacts. IDEAS 7. https://doi.org/10.4000/ideas.1398.
Brajer, V., Mead, R.W., 2003. Blue skies in Beijing? Looking at the olympic effect. J. Environ. Dev. 12 (2), 239–263. https://doi.org/10.1177/1070496503012002005.
Briese, R., 2001. Sustaining Sydney: the 'Green Olympics' from a global perspective. Urban Pol. Res. 19 (1), 25–42. https://doi.org/10.1080/08111140108727861.
Brunekreef, B., Holgate, S.T., 2002. Air pollution and health. Lancet 360 (9341), 1233–1242. https://doi.org/10.1016/S0140-6736(02)11274-8.
Carvalho, H.. New WHO global air quality guidelines: more pressure on nations to reduce air pollution levels. https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(21)00287-4/fulltext.
Cerezo-Esteve, S., Inglés, E., Segui-Urbaneja, J., Solanellas, F., 2022. The environmental impact of major sport events (Giga, mega and major): a systematic review from 2000 to 2021. Sustainability 14 (20), 13581. https://doi.org/10.3390/su142013581.
Chen, Y., Jin, G.Z., Kumar, N., Shi, G., 2013. The promise of Beijing: evaluating the impact of the 2008 Olympic Games on air quality. J. Environ. Econ. Manag. 66 (3), 424–443. https://doi.org/10.1016/j.jeem.2013.06.005.
De La Cruz, A.R.H., Dionisio Calderon, E.R., França, B.B., Réquia, W.J., Gioda, A., 2019. Evaluation of the impact of the Rio 2016 Olympic Games on air quality in the city of Rio de Janeiro, Brazil. Atmos. Environ. 203, 206–215. https://doi.org/10.1016/j.atmosenv.2019.02.007.
Death, C., 2011. 'Greening' the 2010 FIFA world cup: environmental sustainability and the mega-event in South Africa. J. Environ. Pol. Plann. 13 (2), 99–117. https://doi.org/10.1080/1523908x.2011.572656.
Dick, C.D., Wang, Q., 2010. The economic impact of the Olympic Games: evidence from stock markets. Appl. Econ. Lett. 17 (9), 861–864. https://doi.org/10.1080/13504850802552291.
Dominici, F., Peng, R.D., Barr, C.D., Bell, M.L., 2010. Protecting human health from air pollution: shifting from a single-pollutant to a multipollutant approach. Epidemiology 21 (2), 187–194. https://doi.org/10.1097/ede.0b013e3181cc86e8.
Ehrlich, C., Noll, G., Kalkoff, W., Baumbach, G., Dreiseidler, A., 2007. PM10, PM2.5 and PM1.0—Emissions from industrial plants—Results from measurement programmes in Germany. Atmos. Environ. 41 (29), 6236–6254. https://doi.org/10.1016/j.atmosenv.2007.03.059.
Essex, S., Chalkley, B., 2004. Mega-sporting events in urban and regional policy: a history of the Winter Olympics. Plan. Perspect. 19 (2), 201–204. https://doi.org/10.1080/0266543042000192475.
Fang, X., Li, R., Xu, Q., Bottai, M., Fang, F., Cao, Y., 2016. A two-stage method to estimate the contribution of road traffic to PM2.5 concentrations in Beijing, China. Int. J. Environ. Res. Publ. Health 13 (1), 124. https://doi.org/10.3390/ijerph13010124.
Huang, D., Andersson, H., Zhang, S., 2018. Willingness to pay to reduce health risks related to air quality: evidence from a choice experiment survey in Beijing. J. Environ. Plann. Manag. 61 (12), 2207–2229.
Jiang, Y., Yu, S., Chen, X., Zhang, Y., Li, M., Li, Z., Song, Z., Li, P., Zhang, X., Lichtfouse, E., Rosenfeld, D., 2024. Large contributions of emission reductions and meteorological conditions to the abatement of PM2.5 in Beijing during the 24th Winter Olympic Games in 2022. J. Environ. Sci. 136, 172–188. https://doi.org/10.1016/j.jes.2022.12.017.
Jin, L., Zhang, J.J., Ma, X., Connaughton, D.P., 2011. Residents' perceptions of environmental impacts of the 2008 Beijing Green Olympic games. Eur. Sport Manag. Q. 11 (3), 275–300. https://doi.org/10.1080/16184742.2011.577791.
Kansal, A., Khare, M., Sharma, C.S., 2009. Health benefits valuation of regulatory intervention for air pollution control in thermal power plants in Delhi, India. J. Environ. Plann. Manag. 52 (7), 881–899.
Kassens-Noor, E., Lauermann, J., 2017. How to bid better for the olympics: a participatory mega-event planning strategy for local legacies. J. Am. Plann. Assoc. 83 (4), 335–345. https://doi.org/10.1080/01944363.2017.1361857.
Li, B., Wang, F., Yin, H., Li, X., 2019. Mega events and urban air quality improvement. J. Clean. Prod. 217, 116–126. https://doi.org/10.1016/j.jclepro.2019.01.116.
Li, S., Lu, S., Xu, X., Zhao, N., Li, A., Xu, L., 2021. How human mega-events influence urban airborne PM2.5 pollution: a systematic review and meta-analysis. Environ. Pollut. 281, 117009. https://doi.org/10.1016/j.envpol.2021.117009.
Li, Y., Wang, W., Wang, J., Zhang, X., Lin, W., Yang, Y., 2011. Impact of air pollution control measures and weather conditions on asthma during the 2008 Summer Olympic Games in Beijing. Int. J. Biometeorol. 55 (4), 547–554. https://doi.org/10.1007/s00484-010-0373-6.
Liu, Q., Huang, J., Guo, B., Guo, X., 2016. Efficiency of emission control measures on particulate matter-related health impacts and economic cost during the 2014 Asia-Pacific economic cooperation meeting in Beijing. Int. J. Environ. Res. Publ. Health 14 (1), 19. https://doi.org/10.3390/ijerph14010019.
Ma, X., Li, C., Dong, X., Liao, H., 2020. Empirical analysis on the effectiveness of air quality control measures during mega events: evidence from Beijing, China. J. Clean. Prod. 271, 122536. https://doi.org/10.1016/j.jclepro.2020.122536.
MacKinlay, A.C., 1997. Event studies in economics and finance. J. Econ. Lit. 35 (1), 13–39.
Milton, K., Grix, J., 2015. Public health policy and walking in England—Analysis of the 2008 'policy window.'. BMC Publ. Health 15 (1). https://doi.org/10.1186/s12889-015-1915-y.
Mol, A.P.J., 2010. Sustainability as global attractor: the greening of the 2008 Beijing Olympics. Glob. Netw. 10 (4), 510–528. https://doi.org/10.1111/j.1471-0374.2010.00289.x.
Mol, A.P.J., Sonnenfeld, D.A., 2000. Ecological modernisation around the world: an introduction. Environ. Polit. 9 (1), 1–14. https://doi.org/10.1080/09644010008414510.
Müller, M., Gaffney, C., 2018. Comparing the Urban Impacts of the FIFA World Cup and Olympic Games from 2010 to 2016. J. Sport Soc. Issues 42 (4), 247–269. https://doi.org/10.1177/0193723518771830.
O'Brien, D., Chalip, L., 2008. Sport events and strategic leveraging: pushing towards the triple bottom line. In: Woodside, A.G., Martin, D. (Eds.), Tourism Management: Analysis, Behaviour and Strategy, first ed. CAB International, pp. 318–338. https://doi.org/10.1079/9781845933234.0318.
Paquette, J., Stevens, J., Mallen, C., 2011. The interpretation of environmental sustainability by the International Olympic Committee and organizing committees of the olympic games from 1994 to 2008. Sport Soc. 14 (3), 355–369. https://doi.org/10.1080/17430437.2011.557272.
Pui, D.Y.H., Chen, S.-C., Zuo, Z., 2014. PM 2.5 in China: measurements, sources, visibility and health effects, and mitigation. Particuology 13, 1–26. https://doi.org/10.1016/j.partic.2013.11.001.
Rogge, W.F., Hildemann, L.M., Mazurek, M.A., Cass, G.R., Simoneit, B.R.T., 1993. Sources of fine organic aerosol. 2. Noncatalyst and catalyst-equipped automobiles and heavy-duty diesel trucks. Environ. Sci. Technol. 27 (4), 636–651. https://doi.org/10.1021/es00041a007.
Scandizzo, P.L., Pierleoni, M.R., 2018. Assessing the olympic games: the economic impact and beyond. J. Econ. Surv. 32 (3), 649–682.
Schulenkorf, N., Welty Peachey, J., Chen, G., Hergesell, A., 2024. Event leverage: a systematic literature review and new research agenda. Eur. Sport Manag. Q. 24 (3), 785–809. https://doi.org/10.1080/16184742.2022.2160477.
Shen, Y., Ahlers, A.L., 2019. Blue sky fabrication in China: science-policy integration in air pollution regulation campaigns for mega-events. Environ. Sci. Pol. 94, 135–142. https://doi.org/10.1016/j.envsci.2018.12.005.
Smith, A., 2014. Leveraging sport mega-events: new model or convenient justification? J. Policy Res. Tour. Leis. Events 6 (1), 15–30. https://doi.org/10.1080/19407963.2013.823976.
Sorescu, A., Warren, N.L., Ertekin, L., 2017. Event study methodology in the marketing literature: an overview. J. Acad. Market. Sci. 45 (2), 186–207. https://doi.org/10.1007/s11747-017-0516-y.
Streets, D.G., Fu, J.S., Jang, C.J., Hao, J., He, K., Tang, X., Zhang, Y., Wang, Z., Li, Z., Zhang, Q., Wang, L., Wang, B., Yu, C., 2007. Air quality during the 2008 Beijing Olympic Games. Atmos. Environ. 41 (3), 480–492. https://doi.org/10.1016/j.atmosenv.2006.08.046.
Traversi, D., Degan, R., De Marco, R., Gilli, G., Pignata, C., Ponzio, M., Rava, M., Sessarego, F., Villani, S., Bono, R., 2008. Mutagenic properties of PM2.5 air pollution in the Padana Plain (Italy) before and in the course of XX Winter Olympic Games of "Torino 2006.". Environ. Int. 34 (7), 966–970. https://doi.org/10.1016/j.envint.2008.02.007.
Wang, S., Zhao, M., Xing, J., Wu, Y., Zhou, Y., Lei, Y., He, K., Fu, L., Hao, J., 2010. Quantifying the air pollutants emission reduction during the 2008 olympic games in Beijing. Environ. Sci. Technol. 44 (7), 2490–2496. https://doi.org/10.1021/es9028167.
Watanabe, N., Yan, G., McLeod, C., 2023. The impact of sporting events on air pollution: an empirical examination of National Football League Games. Sustainability 15 (6), 5568. https://doi.org/10.3390/su15065568.

Yan, H., Ding, G., Li, H., Wang, Y., Zhang, L., Shen, Q., Feng, K., 2019. Field evaluation of the dust impacts from construction sites on surrounding areas: a city case study in China. Sustainability 11 (7), 1906. https://doi.org/10.3390/su11071906.

Zhan, D., Kwan, M.-P., Zhang, W., Yu, X., Meng, B., Liu, Q., 2018. The driving factors of air quality index in China. J. Clean. Prod. 197, 1342–1351. https://doi.org/10.1016/j.jclepro.2018.06.108.

Zhang, H., Wang, S., Hao, J., Wang, X., Wang, S., Chai, F., Li, M., 2016. Air pollution and control action in Beijing. J. Clean. Prod. 112, 1519–1527. https://doi.org/10.1016/j.jclepro.2015.04.092.

Zhu, Y., Huang, L., Li, J., Ying, Q., Zhang, H., Liu, X., Liao, H., Li, N., Liu, Z., Mao, Y., Fang, H., Hu, J., 2018. Sources of particulate matter in China: insights from source apportionment studies published in 1987–2017. Environ. Int. 115, 343–357. https://doi.org/10.1016/j.envint.2018.03.037.