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HERITAGE TOURISM REVITALIZATION AND URBAN AIR QUALITY: ASSESSING ENVIRONMENTAL TRADE-OFFS IN URBAN DISTRICTS

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Abstract

Urban heritage revitalization has increasingly been adopted as a strategy to stimulate economic growth and enhance city attractiveness through tourism development. However, such functional transformations may also generate environmental pressures, particularly on urban air quality, creating potential trade-offs between economic benefits and environmental sustainability. This study aims to assess the impact of heritage tourism revitalization on air pollutant concentrations and to identify the key factors contributing to air quality degradation in urban districts. A mixed-methods case study was conducted through indoor–outdoor air quality measurements, field observations, interviews, and documentation in the Kayutangan heritage corridor, Malang City, Indonesia, serving as an empirical setting. Data were analyzed using the Miles–Huberman model and Greenship Existing Building version 1.1 parameters focusing on Indoor Health and Comfort. The results indicate that increased traffic density, tourist activity, and commercial operations significantly elevated CO_2, TVOC, and formaldehyde concentrations, with several measurements exceeding recommended health standards. These findings demonstrate the environmental trade-offs associated with heritage tourism revitalization and highlight the need for integrated transportation management, emission control, and continuous air quality monitoring to ensure sustainable urban development.

Keywords: Air Pollution, Greenship, Heritage Revitalization, Sustainable Tourism, Urban Air Quality

Introduction

Urban heritage revitalization has increasingly been adopted as a strategy to stimulate local economic growth, enhance city branding, and improve community welfare through tourism-oriented development (Faghrezi & Setiawan, 2022). By preserving historical and cultural assets while reorganizing public spaces, many cities transform deteriorated urban corridors into attractive heritage destinations. Such initiatives are widely recognized as an effective approach to urban regeneration and economic revitalization.

However, the functional transformation of tourism areas does not only produce socio-economic benefits but also generates environmental consequences. Environmental quality, particularly air quality, has become an increasingly critical factor in determining the sustainability of urban tourism destinations (Eusébio et al., 2023). Poor air conditions may reduce visitors' comfort, satisfaction, and overall travel experience, ultimately influencing their perception of a destination's attractiveness (Bacos et al., 2024). This condition reflects an environmental trade-off, where intensified tourism and economic activities may simultaneously increase environmental pressures and reduce urban livability.

Rapid growth in tourist arrivals typically leads to higher transportation demand and increased motor vehicle traffic, especially in compact heritage corridors with limited road capacity. In many revitalized urban corridors, traffic intensification becomes more pronounced due to directional flow adjustments, pedestrian concentration, and mixed vehicle composition. Empirical studies on one-way urban corridors demonstrate that increased traffic density in constrained urban streets significantly reshapes mobility patterns and elevates vehicular concentration levels (Herjuna et al., 2026). This situation contributes directly to the accumulation of vehicle emissions, including carbon monoxide, nitrogen oxides, and particulate matter, which are known to degrade urban air quality. Empirical evidence indicates that tourism expansion in urban areas is often associated with higher concentrations of air pollutants due to intensified mobility and energy consumption (Zhang et al., 2020).

In addition to traffic-related emissions, commercial and recreational activities within tourism districts may generate secondary pollution sources such as solid waste, cooking smoke, and operational emissions from small businesses (Eusébio et al., 2023). Without proper environmental management, these activities can exacerbate pollution levels and reduce environmental comfort. Previous studies emphasize that environmental pressures resulting from tourism growth must be addressed through effective control measures to prevent long-term ecological degradation (Fan et al., 2022).

From a policy perspective, integrating tourism development with environmental protection has become a central challenge for many global cities. Major tourism destinations such as Barcelona, Venice, Bangkok, and Kyoto have experienced increasing environmental pressures associated with tourism growth, including traffic congestion, air pollution, overcrowding, and degradation of urban livability. These challenges illustrate that balancing tourism-driven economic benefits with environmental sustainability has become a global urban governance issue. Sustainable tourism management requires coordinated strategies, including traffic regulation, pedestrianization, low-emission transportation systems, and green infrastructure development. Destinations that successfully implement such measures tend to maintain better environmental quality while sustaining their tourism competitiveness (Bacos et al., 2024). For example, Copenhagen has integrated bicycle-oriented mobility systems and low-emission transportation policies into its tourism management, while Singapore has strengthened green infrastructure and strict urban environmental regulation within tourism districts. Similarly, Amsterdam has implemented pedestrian prioritization and visitor management strategies to reduce environmental pressure in heritage tourism areas. These examples demonstrate that tourism competitiveness can coexist with environmental protection when supported by integrated urban sustainability policies.

Furthermore, research highlights a reciprocal relationship between tourism intensity and environmental quality. While tourism drives economic growth, unmanaged visitation may gradually deteriorate environmental conditions, which in turn reduces destination appeal and visitor loyalty. Declining air quality not only affects residents' health but also discourages environmentally conscious tourists, thereby threatening the long-term viability of the tourism sector (Zhang et al., 2020). Despite these concerns, empirical investigations that directly measure indoor–outdoor air pollutant dynamics in revitalized heritage districts remain relatively limited, particularly at the micro-urban corridor scale. Corridor-scale analysis is important because heritage tourism corridors represent highly concentrated micro-environments where pedestrian density, vehicle movement, street vending, and semi-enclosed commercial activities interact simultaneously within narrow spatial configurations. Such spatial characteristics can intensify pollutant accumulation and create localized exposure patterns that are often not captured by city-scale air quality monitoring systems. Moreover, indoor–outdoor interaction in corridor environments is critical because pollutants generated outdoors may infiltrate cafés, shops, galleries, and other tourism facilities, thereby increasing public exposure risks in both open and enclosed spaces.

One prominent example of such transformation can be observed in the Kayutangan Heritage area in Malang City, Indonesia. Since 2018, the Malang City Government has revitalized this corridor through façade restoration, pedestrian enhancement, and public space development, converting it from a deteriorated settlement and informal commercial zone into a well-organized heritage tourism destination (Faghrezi & Setiawan, 2022; Khubiyah et al., 2025). Similar pedestrian-oriented revitalization initiatives have also been implemented in several other cities, such as the pedestrian redevelopment of Seoul through the Cheonggyecheon urban restoration project, the transformation of historic corridors in Melaka, and heritage pedestrian enhancement programs in George Town and Kyoto. These cases indicate that pedestrian-based heritage revitalization has become a widely adopted urban strategy, making the environmental implications observed in Kayutangan potentially relevant to other tourism-oriented heritage corridors. The rapid increase in tourism activities, traffic density, and commercial operations makes this area an appropriate empirical setting to assess the environmental consequences of heritage revitalization.

Considering these issues, an empirical investigation is necessary to evaluate how changes in land-use function and tourism activities influence air quality conditions in heritage districts. Therefore, this study aims to assess the environmental trade-offs associated with heritage tourism revitalization by analyzing changes in air pollutant concentrations and identifying the main contributing factors using a mixed-methods approach. The findings are expected to support evidence-based policymaking that balances economic development with environmental preservation in urban heritage destinations (Bacos et al., 2024; Fan et al., 2022).

Research Methods

This study employed a mixed-methods approach with a case study design conducted in the Kayutangan Heritage area, Malang City, Indonesia, during January 2026. Field observations and air quality measurements were conducted over seven consecutive days to capture daily tourism and traffic activity patterns within the heritage corridor. Measurements were carried out at three representative periods of the day, namely morning (07:00–09:00), midday (12:00–14:00), and nighttime (19:00–21:00), in order to identify temporal variations in pollutant concentrations during different levels of tourism and commercial intensity.

The research subjects consisted of visitors, local business owners, café operators, and area managers who were directly involved in tourism and commercial activities within the Kayutangan Heritage corridor. Semi-structured interviews were conducted with these stakeholders to obtain contextual information regarding visitor density, traffic conditions, commercial operational intensity, ventilation practices, and perceived environmental changes after revitalization. The interview component was necessary to support the interpretation of quantitative air quality measurements and to identify potential anthropogenic sources contributing to pollutant accumulation.

Data collection included field observations, indoor–outdoor air quality measurements, interviews, and documentation. The air quality parameters measured consisted of carbon dioxide (CO_2), total volatile organic compounds (TVOC), formaldehyde (HCHO), temperature, and relative humidity (RH). These parameters were selected because they represent key indicators of ventilation quality, chemical pollutant exposure, thermal comfort, and indoor environmental health commonly used in urban environmental assessment and Greenship Existing Building version 1.1 standards, particularly under the Indoor Health and Comfort category.

Indoor air quality measurements were conducted in enclosed or semi-enclosed tourism-supporting facilities located directly along the heritage corridor, including cafés, souvenir shops, and visitor waiting areas with high pedestrian interaction. Outdoor measurements were conducted on the adjacent pedestrian corridor and roadside sections characterized by intensive tourism mobility and mixed traffic activity. Measurements were obtained using portable real-time air quality monitoring devices positioned approximately 1.2–1.5 meters above ground level to represent human breathing height. Each measurement session lasted approximately 15–20 minutes after instrument stabilization to ensure data consistency between indoor and outdoor environments.

Qualitative and quantitative data were analyzed using the Miles–Huberman interactive analysis model through data reduction, data display, and conclusion drawing. Quantitative pollutant measurements were compared across temporal observation periods and spatial environments (indoor–outdoor), while qualitative interview findings were used to interpret the relationship between tourism activities, traffic intensity, commercial operations, and changes in pollutant concentrations within the revitalized heritage corridor.

Research Results and Discussion

Air quality measurements were conducted at different times of the day to capture temporal variations in pollutant concentrations within the Kayutangan Heritage area. Kayutangan Heritage represents one of the most intensively revitalized urban heritage corridors in Malang City, functioning simultaneously as a pedestrian tourism destination, commercial corridor, culinary area, and mixed traffic route. Since the revitalization program initiated by the Malang City Government, the area has experienced substantial increases in visitor activity, roadside commercial operations, and vehicle circulation, making it an important case for evaluating environmental trade-offs associated with tourism-oriented urban transformation. Before revitalization, the corridor primarily consisted of deteriorated residential buildings, informal commercial spaces, limited pedestrian facilities, and relatively low tourism activity. After revitalization, the area was transformed into a structured heritage tourism corridor characterized by widened pedestrian paths, façade restoration, decorative lighting, tourism-supporting businesses, and intensified public activities.

To clarify the transformation process, Table X presents the general comparison between pre- and post-revitalization conditions in the Kayutangan Heritage corridor.

Table 1. General Conditions Before and After Revitalization in Kayutangan Heritage

Aspect	Before Revitalization	After Revitalization
Main Function	Residential and informal commercial corridor	Heritage tourism and commercial corridor
Pedestrian Facilities	Limited and discontinuous pedestrian paths	Wider, organized, and pedestrian-oriented pathways
Tourism Activity	Relatively low tourism activity	High visitor intensity and tourism concentration
Commercial Activity	Small-scale local shops and informal vendors	Cafés, souvenir shops, restaurants, and culinary tourism businesses

Traffic Characteristics	Moderate local traffic dominated by residents	Increased mixed traffic from tourists, private vehicles, motorcycles, and ride-hailing transport
Public Space Quality	Deteriorated urban environment with limited public amenities	Improved aesthetic environment with heritage façade restoration, decorative lighting, and public seating
Building Condition	Several old buildings poorly maintained	Restored heritage façades and adaptive reuse of buildings
Environmental Pressure	Relatively low emission and pedestrian density	Higher pollutant exposure due to tourism and commercial intensification
Economic Activity	Mainly neighborhood-scale economic activity	Tourism-oriented economic growth and commercial expansion

The parameters observed included carbon dioxide (CO_2), total volatile organic compounds (TVOC), formaldehyde (HCHO), temperature, and relative humidity for both indoor and outdoor environments. These parameters were selected because they represent key indicators of urban environmental quality, ventilation conditions, chemical pollutant exposure, and human thermal comfort. CO_2 was measured as an indicator of occupancy density, traffic intensity, and ventilation performance, while TVOC and HCHO were included because they reflect chemical pollutants commonly generated from vehicle exhaust, cooking activities, commercial operations, and building materials in mixed-use tourism environments. Temperature and relative humidity were additionally measured to evaluate thermal comfort conditions that may influence pollutant accumulation and visitor exposure.

Measurements were conducted during three observation periods: morning (07:00–09:00), midday (12:00–14:00), and nighttime (19:00–21:00). During the morning survey period, pedestrian activity and traffic density remained relatively low, consisting mainly of local residents, workers, and limited tourism activity. Vehicle circulation was still moderate, and most cafés and tourism-supporting businesses had not yet reached peak operational intensity. Midday observations represented the peak tourism and commercial period, characterized by dense pedestrian movement, high roadside parking turnover, increased culinary activity, and substantial mixed traffic congestion involving motorcycles, private vehicles, ride-hailing transport, and tourism visitors. Meanwhile, nighttime observations showed moderate tourism activity dominated by culinary visitors and recreational pedestrians, although traffic density remained lower than the midday peak period.

Morning measurements indicated very low pollutant levels, representing baseline environmental conditions with minimal anthropogenic pressure. Indoor CO_2 concentration was recorded at 355 ppm, while outdoor levels reached 405 ppm. TVOC concentrations remained within low exposure levels (0.010–0.017 mg/m^3), far below the commonly recommended indoor guideline threshold of 0.30 mg/m^3, and no detectable formaldehyde was observed. Thermal conditions were also within the recommended comfort range, with temperatures between 24–26°C and relative humidity between 55–65%. These findings suggest that limited traffic movement, lower pedestrian density, and minimal commercial emissions during the morning period contributed to relatively stable environmental conditions.

In contrast, measurements conducted during midday (12:00–14:00) demonstrated the highest pollutant concentrations across all observed parameters. Indoor CO_2 increased substantially to 1350 ppm, while outdoor CO_2 reached 1443 ppm, both exceeding the recommended comfort threshold of 1000 ppm. TVOC concentrations rose to 0.227 mg/m^3 indoors and 0.386 mg/m^3 outdoors, with outdoor concentrations surpassing the commonly accepted air quality guideline of 0.30 mg/m^3. Formaldehyde levels also increased considerably, reaching 0.127 mg/m^3 indoors and 0.165 mg/m^3 outdoors, exceeding the WHO-recommended guideline of 0.10 mg/m³. Additionally, temperature and relative humidity increased to 28–30°C and 75–80%, respectively, indicating declining thermal comfort conditions.

The midday period also corresponded with the highest observed tourism intensity within the corridor. Field observations recorded dense pedestrian concentration, high occupancy levels in cafés and souvenir shops, roadside parking accumulation, and slow-moving traffic conditions. Compared with morning conditions, vehicle density during midday was estimated to increase by approximately two to three times, while visitor concentration became highly concentrated around culinary and heritage attraction points. This condition demonstrates a clear environmental trade-off in which increased tourism and commercial activity simultaneously intensified pollutant accumulation within the heritage corridor environment.

Nighttime observations showed moderate increases in pollutant levels compared with the morning period, although concentrations remained lower than midday conditions. Outdoor CO_2 reached 933 ppm, with TVOC concentrations of 0.293 mg/m³ and formaldehyde at 0.052 mg/m³. Indoor conditions remained relatively lower, with CO_2 at 495 ppm and minimal chemical pollutant accumulation. The nighttime condition reflected residual tourism and culinary activities combined with moderate traffic movement, particularly from recreational visitors and roadside commercial operations. However, reduced solar radiation and lower pedestrian density compared with midday likely contributed to less severe pollutant accumulation.

Overall, the temporal comparison demonstrates a strong relationship between tourism activity intensity, traffic density, and deteriorating air quality conditions within the Kayutangan Heritage corridor. Pollutant concentrations consistently increased during periods characterized by higher visitor density, intensified commercial operations, and heavier transportation activity. These findings indicate that the revitalization of heritage tourism areas may produce measurable environmental consequences at the micro-corridor scale, particularly when increased tourism intensity is not accompanied by adequate emission control and environmental management strategies.

A comparison across time periods shows a clear escalation in pollutant concentrations from morning to midday. CO_2 levels increased by nearly four times indoors and more than three times outdoors. Similar upward trends were observed for TVOC and HCHO concentrations. The difference between indoor and outdoor measurements was consistently present, with outdoor values generally higher for most chemical parameters, although both environments exhibited peak concentrations during midday.

Overall, the results indicate a distinct temporal pattern in which pollutant concentrations were lowest in the morning, moderate at night, and highest during midday for both indoor and outdoor environments. This pattern was consistently observed across all measured parameters. A complete comparison of measurements is presented in Table 1.

Table 2. Indoor–outdoor air quality measurements at different times of day

Time	Location	Standard					Results				
		CO_2 (ppm)	TVOC (mg/m³)	HCHO (mg/m³)	Temp. (°C)	RH (%)	CO_2 (ppm)	TVOC (mg/m³)	HCHO (mg/m³)	Temp. (°C)	RH (%)
Morning	Indoor	< 1000	< 0.30	< 0.10	23–27	40–60	355	0.010	0.000	24	55
Morning	Outdoor						405	0.017	0.000	26	65
Midday	Indoor						1350	0.227	0.127	30	75
Midday	Outdoor						1443	0.386	0.165	28	80
Night*	Indoor						495	0.019	0.008	30	68
Night*	Outdoor						933	0.293	0.052	24	63

(Measurements were conducted in January 2026. Standards/Guidelines: CO_2 < 1000 ppm (ASHRAE, 2020); TVOC < 0.30 mg/m³ (IAQ guideline); HCHO < 0.10 mg/m³ (WHO, 2021); Temperature 23–27°C and Relative Humidity 40–60% for thermal comfort.)

Following the summary presented in Table 1, the temporal distribution of pollutant concentrations becomes more evident when visualized graphically. The comparison between indoor and outdoor measurements highlights substantial fluctuations in air quality across different times of the day, particularly for carbon dioxide (CO_2), which serves as an indicator of human activity intensity and ventilation performance.

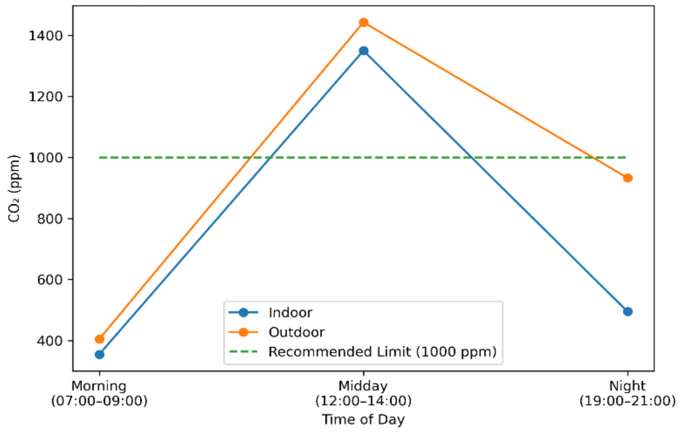

Figure 2. Temporal variation of indoor and outdoor CO_2 concentrations in the Kayutangan Heritage area across different measurement periods

As illustrated in Figure 2, both indoor and outdoor CO_2 concentrations exhibited a clear temporal pattern across the three measurement periods: morning (07:00–09:00), midday (12:00–14:00), and nighttime (19:00–21:00). Morning concentrations remained relatively low, ranging from 355 ppm indoors to 405 ppm outdoors, indicating near-background environmental conditions characterized by lower pedestrian density, limited tourism activity, and adequate air circulation. Similar conditions have been reported in urban environmental studies where lower morning traffic intensity contributes to reduced carbon accumulation in pedestrian corridors (Borrego et al., 2006; Song et al., 2019).

The highest concentrations were observed during the midday period, when indoor CO_2 increased sharply to 1350 ppm and outdoor concentrations reached 1443 ppm. Both values exceeded the recommended indoor air quality threshold of 1000 ppm established by ASHRAE (2020), as indicated by the dashed guideline line in Figure 2. This substantial increase corresponded with peak tourism intensity, dense pedestrian movement, intensified commercial operations, and heavy mixed traffic conditions within the Kayutangan Heritage corridor. Previous studies similarly demonstrate that tourism concentration, traffic congestion, and mixed commercial activities significantly elevate urban CO_2 accumulation in heritage and tourism districts (Eusébio et al., 2020; Silva & Henriques, 2021; Zhang & Lu, 2022).

During nighttime observations, CO_2 concentrations decreased compared with midday conditions but remained higher than morning levels, particularly in outdoor environments. Outdoor CO_2 reached 933 ppm, while indoor concentrations declined to 495 ppm, suggesting the persistence of residual tourism and traffic-related emissions during evening recreational activities. Comparable nighttime pollutant retention patterns have also been identified in compact urban corridors with ongoing evening commercial activity and reduced atmospheric dispersion (Liu et al., 2025; Petrus & Popa, 2024). Overall, the temporal trend shown in Figure 2 demonstrates a strong relationship between tourism-related urban activity intensity and deteriorating air quality conditions within the revitalized heritage corridor.

This pattern suggests that intensified tourism, commercial activities, and vehicle density during peak hours significantly contributed to the accumulation of carbon emissions within the study area. However, it is important to note that elevated midday pollutant concentrations may also occur in other high-density urban pedestrian corridors that are not specifically tourism-oriented. Therefore, the findings in Kayutangan Heritage should be interpreted as reflecting the combined effects of tourism intensity, mixed commercial activity, pedestrian concentration, and traffic congestion within a compact urban corridor environment rather than tourism activity alone. Nevertheless, the pollutant escalation observed in this study appears to be reinforced by the tourism-oriented functional transformation of the corridor, particularly through intensified visitor mobility, roadside commercial operations, and prolonged pedestrian occupation during peak hours. Similar increases in urban CO_2 concentrations associated with traffic congestion and tourism-related mobility have been reported in several heritage and commercial districts worldwide, including the Jerónimos Monastery tourism area in Lisbon (Silva & Henriques, 2021), urban tourism corridors in Aveiro (Eusébio et al., 2020), mixed commercial streets in urban functional zones in Beijing and the Yangtze River Delta region (Song et al., 2019; Zhang & Lu, 2022), as well as traffic-dense pedestrian environments in Bucharest and other European urban corridors (Petrus & Popa, 2024). Traffic-related pollutant accumulation in compact urban streets has also been widely documented in general urban transport studies (Borrego et al., 2006; Liu et al., 2026).

Therefore, although the temporal increase in pollutant concentrations observed in Kayutangan Heritage may partly reflect broader urban traffic dynamics commonly found in pedestrian corridors, the tourism-driven intensification of commercial and mobility activities likely amplified environmental pressure within the revitalized heritage area. The consistently higher outdoor concentrations further indicate that traffic-related sources represent the dominant contributor to local air pollution, while indoor spaces partially buffer exposure through enclosure and limited infiltration, as observed in previous urban microclimate studies (Morawska et al., 2021). Overall, the graphical trend in Figure 3 confirms the temporal relationship between human activity intensity and declining air quality conditions in the Kayutangan Heritage environment.

In addition to carbon dioxide, the concentration of total volatile organic compounds (TVOC) provides further insight into the presence of chemical pollutants associated with commercial activities, fuel combustion, and building-related emissions. While CO_2 primarily reflects occupancy and ventilation conditions, TVOC indicates the accumulation of organic chemical substances that may pose greater health risks even at relatively low concentrations (ASHRAE, 2020); (Salthammer et al., 2010); (Wei et al., 2023). Elevated TVOC levels in mixed-use urban and tourism areas have also been documented as a consequence of cooking emissions, street vending, and vehicle exhaust (Andriani, 2011; Saputra & Ekawati, 2017; Weinstein et al., 2017), reinforcing the interpretation of anthropogenic sources in the present study.

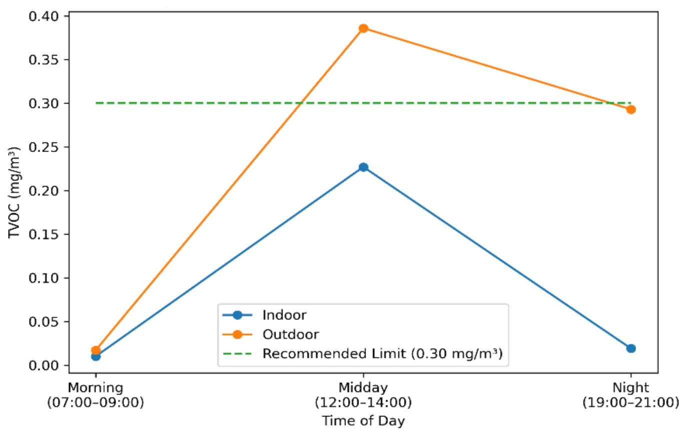

Figure 3. Comparison of indoor and outdoor TVOC concentrations across different measurement periods in the Kayutangan Heritage area

As presented in Figure 3, TVOC concentrations exhibited a clear temporal variation across the three measurement periods: morning (07:00–09:00), midday (12:00–14:00), and nighttime (19:00–21:00). Similar to the CO_2 pattern, both indoor and outdoor TVOC concentrations increased substantially from morning to midday before declining again at night. Morning measurements showed very low concentrations ranging from 0.010 mg/m³ indoors to 0.017 mg/m³ outdoors, indicating minimal emission sources, lower tourism activity, and effective air circulation during baseline environmental conditions.

The highest concentrations were observed during the midday period, when indoor TVOC increased sharply to 0.227 mg/m³ and outdoor concentrations reached 0.386 mg/m³. As illustrated by the dashed guideline line in Figure 3, the outdoor concentration exceeded the commonly recommended indoor air quality guideline of 0.30 mg/m³ for total volatile organic compounds (TVOC), indicating deteriorated air quality conditions during peak tourism and commercial activity hours (Mølhave, 2004). Field observations during this period also identified dense pedestrian movement, intensive culinary operations, roadside commercial activity, and heavy mixed traffic circulation as potential contributors to pollutant accumulation within the heritage corridor.

During nighttime observations, TVOC concentrations declined compared with midday conditions but remained relatively elevated outdoors at 0.293 mg/m³, approaching the recommended threshold. Indoor nighttime concentrations decreased substantially to 0.019 mg/m³, suggesting that pollutant accumulation indoors remained more controlled due to lower occupancy intensity and limited pollutant infiltration. The persistence of relatively high outdoor nighttime concentrations indicates the continued influence of evening tourism activities, vehicle emissions, and residual commercial operations within the corridor environment (He et al., 2023). Overall, the temporal trend shown in Figure 3 demonstrates that intensified tourism-related mobility and mixed commercial activities significantly contributed to the accumulation of volatile organic pollutants within the Kayutangan Heritage area (Gu et al., 2023; Junlin et al., 2017).

The highest concentrations were observed at midday, when indoor TVOC rose to 0.227 mg/m³ and outdoor levels reached 0.386 mg/m³. Notably, outdoor TVOC concentrations exceeded the commonly recommended guideline of 0.30 mg/m³, indicating deteriorated air quality conditions during peak activity hours. Similar increases in TVOC concentrations during periods of intense commercial and traffic activities have been documented in urban tourism corridors and mixed-use streets, where cooking emissions, street vending, fuel combustion, and vehicle exhaust are identified as dominant anthropogenic sources (Gu et al., 2023; Junlin et al., 2017). This finding confirms that intensified tourism, street vending, food preparation, and vehicle emissions contribute substantially to the release of volatile organic compounds within the heritage corridor. Overall, the graphical trend shown in Figure 4 reinforces the evidence that anthropogenic activities during peak daytime hours significantly elevate chemical pollutant levels, with outdoor environments experiencing greater exposure. Comparable temporal patterns between human mobility and VOC accumulation have also been reported in densely visited public spaces (Al-mudhaf et al., 2013; Wei et al., 2023). These results highlight the need for improved emission control strategies and better ventilation management to minimize the accumulation of hazardous organic compounds in both public and enclosed spaces.

Beyond general volatile organic compounds, formaldehyde (HCHO) was specifically monitored due to its classification as a hazardous air pollutant with recognized adverse health effects, particularly in enclosed or poorly ventilated environments. In urban tourism and mixed-use commercial corridors, HCHO may originate from multiple anthropogenic sources, including vehicle exhaust emissions, cooking activities, tobacco smoke, building materials, furniture coatings, adhesives, paints, and combustion-related commercial operations (Guo et al., 2024; Salthammer et al., 2010; X. Zhou et al., 2025). Compared with CO_2 and TVOC, HCHO is more directly associated with toxic exposure risks, as prolonged inhalation may cause respiratory irritation, eye and throat irritation, asthma aggravation, and long-term health problems including carcinogenic risks and chronic respiratory disorders (Salthammer et al., 2010; WHO, 2021; X. Zhou et al., 2025).

The health risks and indoor accumulation of formaldehyde in commercial and public buildings have been widely emphasized in recent indoor air quality studies and international health guidelines (Salthammer et al., 2010; WHO, 2021; X. Zhou et al., 2025). Therefore, its concentration serves as an important indicator of indoor environmental safety and overall air quality.

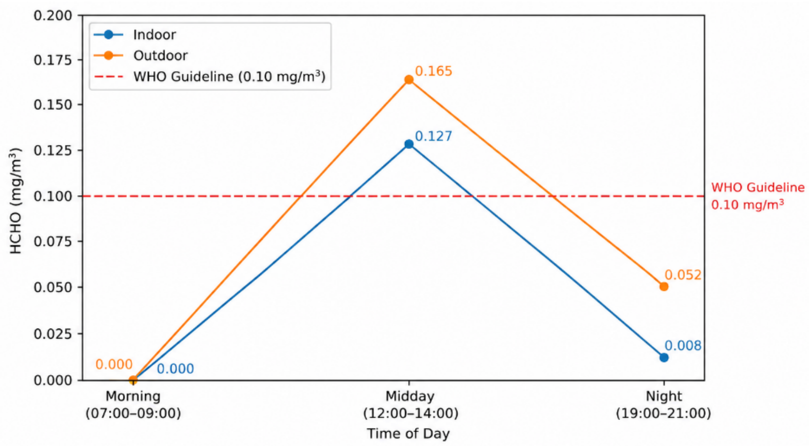

Figure 4. Indoor and outdoor formaldehyde (HCHO) concentration trends across different measurement periods in the Kayutangan Heritage area

As illustrated in Figure 4, formaldehyde (HCHO) concentrations exhibited a clear temporal variation across the three measurement periods: morning (07:00–09:00), midday (12:00–14:00), and nighttime (19:00–21:00). Similar to the previous air quality parameters, HCHO concentrations remained very low during the morning period and increased substantially during midday observations (Guo et al., 2024; Salthammer et al., 2010; X. Zhou et al., 2025). During the morning period, no detectable HCHO was identified in either indoor or outdoor measurements, indicating negligible chemical emission sources, lower anthropogenic activity, and favorable air exchange conditions within the heritage corridor environment.

The highest concentrations were recorded during the midday period, when indoor HCHO concentrations increased sharply to 0.127 mg/m^3 and outdoor concentrations reached 0.165 mg/m^3. As indicated by the dashed guideline line in Figure 4, both values exceeded the World Health Organization (WHO) recommended exposure guideline of 0.10 mg/m^3 for formaldehyde in indoor environments, suggesting potentially unhealthy air quality conditions during peak tourism and traffic activity periods (WHO, 2021). Field observations during midday also identified intensified pedestrian concentration, roadside commercial activity, culinary operations, and heavy mixed traffic circulation, all of which likely contributed to increased formaldehyde emissions within the corridor environment. Similar elevations of formaldehyde concentrations in commercial and mixed-use urban environments have been associated with vehicle exhaust, cooking emissions, building materials, and intensive human activities (Guo et al., 2024; Salthammer et al., 2010).

During nighttime observations (19:00–21:00), HCHO concentrations declined compared with midday conditions but remained detectable outdoors at 0.052 mg/m^3 and minimally indoors at 0.008 mg/m^3. Although these nighttime concentrations remained below the WHO guideline threshold, the persistence of detectable outdoor HCHO levels suggests the continued influence of residual traffic emissions and evening commercial activities within the heritage corridor.

Overall, the temporal pattern presented in Figure 4 confirms that hazardous chemical pollutants accumulated during periods of intensified urban activity, with outdoor environments consistently exhibiting greater exposure than indoor spaces. Nevertheless, indoor environments also exceeded recommended safety thresholds during peak occupancy periods, indicating that enclosed or semi-enclosed tourism-supporting facilities remained vulnerable to pollutant accumulation under crowded conditions. Comparable findings have been reported in recent indoor–outdoor air quality assessments, which demonstrate that limited ventilation, high visitor density, and intensified urban activity significantly worsen pollutant accumulation in public and commercial spaces (Alonso-blanco et al., 2025; Challoner & Gill, 2014; López-Aparicio et al., 2011). These findings emphasize the necessity for improved ventilation systems, emission reduction measures, and integrated environmental management strategies within heritage tourism areas to protect public health while maintaining tourism sustainability.

Overall, these findings directly answer the research objective by demonstrating that the revitalization and intensified tourism activities in Kayutangan Heritage are associated with measurable increases in air pollutant concentrations, particularly during peak daytime hours. The transformation of the area from a predominantly residential corridor into a tourism-oriented commercial zone appears to have altered local activity patterns, including increased pedestrian concentration, commercial operations, and traffic intensity, which may contribute to higher CO_2, TVOC, and HCHO concentrations observed during peak activity periods. However, because this study did not include direct pre-revitalization air quality measurements, the findings should be interpreted as indicating an association between intensified urban tourism activities and pollutant accumulation rather than definitive causal evidence of environmental change after revitalization. Similar increases in urban air pollutants during tourism or commercial peak hours have been reported in previous studies of heritage and pedestrian-commercial districts (Challoner & Gill, 2014; Eusébio et al., 2020; López-Aparicio et al., 2011; Silva & Henriques, 2021; Song et al., 2019; Zhang & Lu, 2022) benefits but also to environmental pressure, especially on urban air quality.

These results imply that heritage-based urban revitalization should be integrated with transportation control, pedestrianization, and low-emission strategies to ensure environmental sustainability. Such integrated approaches have been recommended in recent urban environmental management studies to reduce traffic-related emissions and improve public health outcomes (Jack & Kinney, 2010; Krisdiyanto, 2024; WHO, 2021). Therefore, maintaining environmental quality should become a central consideration in future heritage revitalization policies to balance economic growth with public health protection.

These findings indicate that pollutant accumulation in heritage tourism corridors reflects a structural environmental consequence of land-use transformation and tourism intensification rather than a temporary environmental fluctuation. Therefore, mitigation strategies must prioritize emission source control combined with micro-environmental adaptation approaches to ensure both environmental sustainability and tourism functionality.

Based on the measured midday peak conditions, mitigation strategies should target the reduction of outdoor pollutant influx and indoor accumulation simultaneously. For example, reducing vehicle emission loads during peak tourism hours has the potential to directly lower outdoor TVOC and HCHO exposure, while improving indoor air exchange performance can help prevent pollutant infiltration and accumulation. Previous studies have demonstrated that traffic-related pollutants significantly contribute to indoor and outdoor air quality deterioration in urban environments, particularly in compact commercial and transportation corridors (Chan & Chung, 2003; Chang, 2002). Research by Chang (2002) further showed that optimized ventilation pathways and controlled air exchange systems can effectively reduce the ingress of vehicle-related pollutants into indoor environments. Similarly, studies on indoor air quality management have confirmed that enhanced ventilation systems are effective in reducing volatile organic compounds (VOCs) and formaldehyde accumulation in enclosed spaces (Ciuzas et al., 2016; Hult et al., 2015; Lee et al., 2024). These findings support the argument that integrated emission reduction and ventilation management strategies are essential for minimizing pollutant exposure in revitalized heritage tourism corridors.

Therefore, mitigation strategies should be designed using a source-to-receptor framework, where transportation emission control, pedestrian flow regulation, and building ventilation management are implemented as interconnected systems rather than isolated interventions. From a primary emission control perspective, one critical intervention is the implementation of low-emission vehicle restrictions

Based on the observed pollutant patterns, several targeted environmental control measures can be operationalized within heritage tourism corridors such as Kayutangan. One important intervention is the reduction of vehicle emission intensity during peak tourism periods through traffic management, pedestrian prioritization, low-emission transportation policies, and controlled roadside parking systems. Previous studies have demonstrated that vehicle exhaust emissions significantly contribute to the accumulation of volatile organic compounds (TVOC) and formaldehyde (HCHO) in dense urban commercial environments, particularly in areas characterized by heavy traffic congestion and mixed tourism activities (Guo et al., 2024; Salthammer et al., 2010; X. Zhou et al., 2025). Therefore, limiting traffic density and improving transportation management within heritage tourism corridors may help reduce outdoor pollutant exposure and minimize pollutant infiltration into indoor commercial spaces.

The adoption of similar vehicle filtration criteria in heritage tourism zones could be operationalized through access control mechanisms. For instance, vehicle entry could be restricted to electric vehicles, hybrid vehicles, or combustion vehicles meeting Euro 6-equivalent emission levels. Such standards are proven to substantially reduce NOx and particulate emissions compared to older vehicle generations, making them suitable benchmarks for low-emission tourism corridors (DieselNet, 2024). In high-density pedestrian tourism zones, this restriction could be complemented by last-mile transport solutions such as electric shuttle buses or electric micro-mobility systems.

Beyond transportation interventions, indoor microclimate and pollutant mitigation strategies should be implemented at the building and micro-space scale. Plant-based air remediation represents one complementary strategy, particularly for volatile organic compounds (VOC) and formaldehyde exposure (Dela Cruz et al., 2014; Teiri et al., 2018). However, recent reviews also emphasize that the pollutant removal effectiveness of indoor plants in real-world environments remains relatively limited compared with mechanical ventilation systems and active air filtration technologies (Cummings & Waring, 2020). Experimental evidence demonstrates that certain ornamental plant species can absorb VOCs and improve indoor air quality under controlled conditions. For example, plant-based biofilter systems using ornamental species have shown measurable removal of benzene, toluene, and acetophenone pollutants, suggesting their potential role as passive air purification systems (Alvarado-Alvarado et al., 2025; Choi et al., 2021; Elhadad et al., 2025).

Specific plant species can be strategically selected based on pollutant type. Sansevieria trifasciata (snake plant), for instance, has been experimentally tested for formaldehyde exposure and demonstrates active physiological responses during pollutant uptake, although plant stress may occur at high exposure levels (Alvarado-Alvarado et al., 2025; Li et al., 2024). This indicates that plant-based mitigation is effective as a complementary rather than primary pollution control strategy. Therefore, plant installation density must be calibrated carefully and combined with mechanical ventilation systems.

From an operational perspective, indoor tourism facilities such as cafés, souvenir shops, and visitor waiting areas could incorporate modular plant-based biofilter clusters. Instead of decorative placement, plants should be positioned near emission hotspots such as cooking areas, entry points exposed to traffic pollutants, and enclosed visitor waiting zones. Combining multiple plant species has been shown to improve overall VOC removal efficiency due to differences in pollutant uptake mechanisms (Alvarado-Alvarado et al., 2025; Choi et al., 2021; Elhadad et al., 2025).

In addition to plant-based approaches, micro-ecological cooling strategies such as small indoor water features or micro-pond systems may contribute indirectly to environmental comfort by stabilizing microclimatic conditions, increasing perceived thermal comfort, and supporting humidity regulation within dense urban environments (Manteghi et al., 2015; W. Zhou et al., 2025). Previous studies on urban microclimate design have shown that water-based landscape elements can reduce localized heat stress and improve thermal perception in public spaces, although their direct effects on pollutant reduction remain limited and context-dependent. While not directly removing pollutants, increased humidity can reduce airborne particle suspension and improve human thermal comfort perception, which is important in tropical tourism environments. When combined with shading and vegetation placement, such micro-ecological interventions can enhance perceived environmental quality in semi-indoor heritage tourism spaces.

However, it is important to critically emphasize that indoor plants alone cannot replace ventilation or emission source control. Evidence suggests that while plants can contribute to pollutant reduction in controlled environments, real-world effectiveness depends strongly on plant density, air exchange rate, and pollutant concentration (Alvarado-Alvarado et al., 2025; Choi et al., 2021; Elhadad et al., 2025). Therefore, plant-based mitigation must be integrated into a broader environmental management system that includes ventilation optimization, emission source reduction, and visitor density management.

In addition to micro-scale indoor vegetation strategies, macro-scale urban vegetation planning also plays an important role in supporting environmental mitigation within heritage tourism corridors. The integration of functional urban tree species such as *Mimusops elengi*, *Polyalthia longifolia*, *Mangifera indica*, and *Filicium decipiens* can provide multiple environmental benefits, including solar radiation shading, urban heat reduction, and traffic noise attenuation (Abhijith et al., 2017; Livesley et al., 2016; Pattnaik et al., 2024). Shade-providing tree canopies can reduce surface temperature and indirectly lower secondary pollutant formation associated with photochemical reactions in high solar exposure environments. In addition, dense foliage structures contribute to particulate matter interception and microclimate stabilization along pedestrian tourism corridors (Wibowo et al., 2022).

From an operational urban design perspective, linear tree planting along heritage pedestrian routes and mixed commercial streets can function as environmental buffer zones between traffic emission sources and public activity areas. For example, *Polyalthia longifolia* and *Filicium decipiens* are known for their vertical dense canopy structures, making them suitable for roadside pollution and noise buffering, while *Mimusops elengi* provides broader canopy shading for pedestrian thermal comfort (Abhijith et al., 2017; Livesley et al., 2016; Pattnaik et al., 2024; Russo & Cirella, 2023; Xiao et al., 2025). Meanwhile, productive tree species such as *Mangifera indica* can contribute to urban biodiversity and ecosystem service enhancement while maintaining landscape functionality. Integrating these species into heritage corridor landscape planning may provide long-term passive environmental mitigation that complements technological emission control and indoor environmental management strategies.

From a spatial planning perspective, vegetation density along heritage corridors should be designed to function as a semi-permeable environmental buffer. Linear tree spacing of approximately 6–10 meters per tree along traffic edges can provide continuous shading and pollutant interception without blocking pedestrian airflow circulation, while denser vegetation clusters can be positioned in pedestrian rest nodes to enhance localized microclimate cooling and environmental comfort (Bowler et al., 2010; Morakinyo et al., 2017).

However, it is important to note that urban vegetation functions primarily as a supporting environmental buffer rather than a primary pollutant removal system. Therefore, urban tree integration must be implemented alongside transportation emission control, ventilation management, and visitor density regulation to achieve measurable improvements in urban air quality within high-intensity tourism districts.

From a policy standpoint, heritage revitalization projects should integrate environmental carrying capacity thresholds into tourism planning. Instead of relying solely on visitor volume metrics, environmental performance indicators such as maximum allowable pollutant concentration thresholds during peak tourism hours should be introduced. This approach aligns environmental management directly with tourism activity regulation and enables dynamic policy interventions during high pollution periods.

Overall, these findings suggest that sustainable heritage tourism management must move beyond general environmental recommendations and adopt measurable, technology-supported, and biologically integrated environmental control strategies. Combining transportation emission control, targeted indoor biofiltration using selected plant species, and micro-ecological climate stabilization measures provides a practical multi-layer environmental mitigation model for heritage tourism districts experiencing rapid functional transformation.

Conclusion

This study examined the environmental implications of heritage tourism revitalization in the Kayutangan Heritage corridor, Malang City, by integrating indoor–outdoor air quality measurements with field observations and qualitative interviews. The findings indicate that periods of intensified tourism and commercial activity were associated with increased concentrations of CO_2, TVOC, and formaldehyde (HCHO), particularly during midday conditions when visitor density, roadside commercial operations, and mixed traffic activity reached their peak. Outdoor pollutant concentrations consistently exceeded indoor levels, although indoor environments also surpassed recommended exposure thresholds during crowded periods, indicating that tourism-supporting facilities remain vulnerable to pollutant accumulation under limited ventilation conditions. The study further revealed that the revitalization of the corridor into a tourism-oriented commercial destination was accompanied by substantial changes in environmental activity patterns, including increased pedestrian concentration, traffic intensity, and commercial emissions. Interview results with local business owners and area managers supported these findings, indicating that overcrowding, thermal discomfort, and declining environmental comfort became more noticeable during peak tourism hours after revitalization. These results suggest the existence of environmental trade-offs between tourism-driven economic revitalization and urban environmental quality within heritage districts. The novelty of this study lies in its micro-scale assessment of temporal indoor–outdoor air pollutant dynamics within a revitalized heritage tourism corridor using Greenship-based environmental indicators. By combining quantitative environmental measurements with qualitative contextual observations, this study provides empirical evidence regarding how tourism-oriented land-use transformation may influence environmental exposure conditions in dense urban heritage spaces. From a practical perspective, the findings emphasize the importance of integrating environmental management into heritage tourism planning through transportation emission control, pedestrian flow regulation, ventilation improvement, urban vegetation planning, and real-time environmental monitoring systems. These interventions are essential to reduce pollutant accumulation while maintaining tourism attractiveness and public environmental comfort. Future studies are recommended to conduct long-term monitoring across multiple heritage tourism districts, incorporate broader pollutant parameters, and compare revitalized and non-revitalized pedestrian corridors to strengthen the generalizability of sustainable urban tourism planning frameworks.

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