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Sustainable Urban Green Infrastructure for Air Pollution Mitigation and Environmental Quality Enhancement

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ABSTRACT
Urban areas are increasingly facing critical challenges related to air pollution, declining environmental quality, and rapid urbanization. Sustainable urban green infrastructure (UGI)—including parks, green roofs, vertical gardens, and urban forests—has been recognized as an effective strategy to improve air quality and promote ecological resilience. This study aims to evaluate the role of UGI in mitigating air pollution and enhancing overall environmental quality in metropolitan areas. A mixed-method approach was employed, combining spatial analysis of green infrastructure distribution with air quality monitoring (PM2.5, NO_2, and CO_2 levels) and stakeholder surveys in selected urban districts. The findings indicate that areas with higher proportions of UGI demonstrated a significant reduction in particulate matter (PM2.5) by 18–25% and nitrogen dioxide (NO_2) levels by 12–19%, compared to urban zones with minimal green infrastructure. Additionally, stakeholder perceptions revealed strong correlations between UGI presence and improved thermal comfort, reduced noise levels, and enhanced public well-being. The results highlight that integrating UGI into urban planning not only contributes to pollution reduction but also strengthens climate resilience and supports the achievement of Sustainable Development Goals (SDG 11 and 13). The study emphasizes the need for policymakers and urban planners to prioritize sustainable green infrastructure as a cost-effective and long-term solution to address air pollution and environmental degradation in rapidly urbanizing regions.

INTRODUCTION

Urbanization has become one of the most pressing global challenges, with more than 55% of the world's population currently living in cities, a figure projected to rise to nearly 68% by 2050 (United Nations, 2019). This rapid urban growth has significantly contributed to escalating air pollution, reduced green spaces, and declining environmental quality in metropolitan areas. Air pollution, particularly from particulate matter (PM2.5), nitrogen dioxide (NO_2), and carbon dioxide (CO_2), has been linked to respiratory diseases, premature mortality, and climate change. Addressing these environmental concerns requires innovative, sustainable, and integrative approaches that enhance both ecological and human well-being.

One promising solution is the implementation of sustainable urban green infrastructure (UGI), which includes parks, street trees, urban forests, green roofs, and vertical gardens. Research has demonstrated that UGI can mitigate air pollution by capturing particulate matter, sequestering carbon, and moderating local microclimates (Janhäll, 2015). Additionally, UGI provides co-benefits such as biodiversity enhancement, noise reduction, and improved thermal comfort (Kabisch & Qureshi, 2015; Mullaney et al., 2015). However, despite the increasing recognition of UGI, challenges remain in quantifying its direct contribution to air quality improvement and linking ecological benefits with measurable human health outcomes (Feyisa, 2021; Norton et al., 2015).

Existing studies have often emphasized the ecological and environmental services of UGI in cities across Europe and North America (Livesley et al., 2016; Salmond et al., 2016). Yet, there is a research gap regarding comprehensive evaluations of UGI effectiveness in rapidly urbanizing regions, particularly in developing countries where urban air pollution is severe, and resources for large-scale interventions are limited. Furthermore, the integration of UGI into urban policy frameworks remains inconsistent, with limited empirical evidence on cost-effectiveness and social acceptance (Hartig et al., 2014; Russo et al., 2017).

This article seeks to address these gaps by evaluating the role of sustainable UGI in mitigating air pollution and enhancing environmental quality. Specifically, it aims to (1) analyze the effectiveness of UGI in reducing major air pollutants (PM2.5, NO_2, CO_2), (2) assess the co-benefits of UGI for environmental comfort and public well-being, and (3) provide policy recommendations for urban planners and decision-makers to integrate UGI into sustainable development agendas. By doing so, this study contributes to advancing knowledge on the potential of UGI to improve environmental resilience and support global commitments such as the Sustainable Development Goals (SDG 11: Sustainable Cities and Communities, and SDG 13: Climate Action).

Recent advances in remote sensing technologies and machine learning algorithms have significantly enhanced the capability to map and quantify UGI at various spatial scales. Lyu et al., (2025) employed explainable machine learning models to analyze morphological spatial patterns of UGI across 288 Chinese cities, revealing that smaller non-core UGI areas such as perforations and islets exert more pronounced positive impacts on PM2.5 reduction compared to larger core areas. This finding challenges conventional assumptions about UGI effectiveness and highlights the importance of strategic placement of diverse green infrastructure types. Similarly, Dobrinić et al., (2025) conducted a comprehensive review of materials and learning methods for green infrastructure mapping, demonstrating that deep learning techniques combined with high-resolution satellite imagery can achieve accuracy rates exceeding 90% in urban vegetation classification. These technological advancements enable more precise assessment of UGI distribution and its environmental benefits, facilitating evidence-based urban planning decisions.

Despite technological progress, methodological challenges persist in quantifying UGI benefits across diverse urban contexts. Khalili et al., (2024) conducted a systematic review of methods employed to assess UGI effectiveness in heat mitigation, thermal comfort control, and air quality improvement, identifying substantial variations in monitoring approaches, remote sensing applications, and modeling techniques. Their analysis revealed that while numerous studies have documented UGI's capacity to reduce urban temperatures by 2-8°C and improve air quality by 10-40%, the lack of standardized measurement protocols complicates cross-regional comparisons and meta-analyses. This methodological heterogeneity underscores the need for integrated assessment frameworks that combine ground-based measurements, satellite observations, and simulation models to comprehensively evaluate UGI performance under varying climatic and socioeconomic conditions.

The policy implementation gap remains particularly pronounced in rapidly urbanizing regions of Asia and Africa, where resource constraints and competing development priorities often marginalize UGI investments. Recent evidence from Southeast Asian cities indicates that while national governments have adopted green city frameworks aligned with SDG 11, local-level implementation faces significant barriers including limited technical capacity, inadequate funding mechanisms, and insufficient cross-sectoral coordination. Furthermore, the uneven distribution of UGI often exacerbates environmental injustice, with low-income neighborhoods experiencing significantly less green space coverage and consequently bearing disproportionate health burdens from air pollution and heat stress. Addressing these disparities requires not only increased investment in UGI development but also equitable spatial planning strategies that prioritize underserved communities and integrate community participation in design and maintenance processes.

METHOD

Study Area

The study was conducted in three metropolitan districts characterized by high urban density, limited green spaces, and elevated levels of air pollution. The selected districts represented diverse land-use patterns, including residential, industrial, and commercial zones. These sites were chosen based on air pollution hotspots identified from previous governmental monitoring reports and satellite imagery (Landsat 8 OLI). The climate of the region is classified as tropical monsoon, with average annual temperatures ranging from 26–30 °C and mean rainfall exceeding 2,000 mm per year. The study was conducted in three metropolitan districts in Jakarta Metropolitan Area, Indonesia, specifically in Central Jakarta (Tanah Abang District), East Jakarta (Cakung District), and South Jakarta (Kebayoran Baru District), selected to represent diverse urban characteristics and pollution levels.

Materials

The materials and tools used in this study included:

1. Air quality monitoring devices: Portable sensors for $PM_{2.5}$, PM_{10}, NO_2, and CO_2 (AirVisual Pro, Aeroqual Series 500).
2. Remote sensing and GIS software: ArcGIS 10.8 and QGIS 3.16 for mapping green infrastructure and land-use classification.
3. Vegetation analysis: Normalized Difference Vegetation Index (NDVI) derived from Sentinel-2 imagery.
4. Survey instruments: Structured questionnaires distributed to 300 households in the study area to capture community perceptions of environmental quality.

5. Statistical software: SPSS 26.0 and R 4.2.1 for regression, correlation, and multivariate analysis.

Sampling and Data Collection
Air Quality Monitoring

Air samples were collected at 12 monitoring stations, strategically placed within 100 m of major urban green infrastructure (parks, street trees, and green roofs) and at control sites lacking vegetation. Measurements were taken at 8-hour intervals over a 3-month period (March–May 2024), covering both peak and off-peak traffic hours.

Vegetation and Land-Use Assessment

Green infrastructure distribution was analyzed using NDVI values, with classification thresholds of 0.2–0.5 (moderate vegetation) and >0.5 (dense vegetation). Ground-truthing was performed by conducting field surveys across 25 randomly selected sites. The methodology aligns with best practices established by Di Palma et al., (2024), who demonstrated that combining NDVI analysis with ground-truth validation significantly enhances the accuracy of ecosystem services mapping in urban environments.

Social Perceptions

A stratified random sampling method was applied to distribute questionnaires across three districts, ensuring representation of age, gender, and occupation. Questions covered perceived air quality, environmental comfort (thermal and noise levels), and health-related symptoms associated with pollution exposure.The survey was conducted concurrently with air quality monitoring from March to May 2024, with questionnaire distribution completed within the first two weeks of April 2024.

Analytical Framework

Data analysis was carried out in three stages:

1. Spatial Analysis: GIS-based overlay mapping of UGI distribution and air pollution levels to examine spatial correlations.
2. Statistical Analysis: Pearson correlation and multiple regression models were employed to evaluate the relationship between UGI coverage (independent variable) and pollutant concentrations (dependent variables: $PM_{2.5}$, NO_2, CO_2).
3. Perception Analysis: Survey responses were coded and analyzed using descriptive statistics and factor analysis to identify the perceived benefits of UGI.

Analytical Model

$$Y=\beta 0+\beta 1XUGI+\beta 2XTraffic+\beta 3XIndustrial+\epsilon$$

Where Y represents pollutant concentration, $X_{(UGI)}$ is the proportion of urban green infrastructure, $X_{(Traffic)}$ is vehicular density, and $X_{(Industrial)}$ is the proportion of industrial land use.

Table 1. Summary of Materials and Data Sources

Component	Data/Instrument Used	Source/Specification
Air Quality Data	$PM_{2.5}$, NO_2, CO_2 sensors	AirVisual Pro, Aeroqual 500
Vegetation Cover	NDVI from Sentinel-2, Landsat 8 OLI	ESA, USGS
Land-Use Classification	GIS spatial analysis	ArcGIS 10.8, QGIS 3.16
Survey Data	Structured questionnaires (n=300)	Field survey, 2024
Statistical Analysis	Regression, factor analysis	SPSS 26.0, R 4.2.1

Source: Data Processed

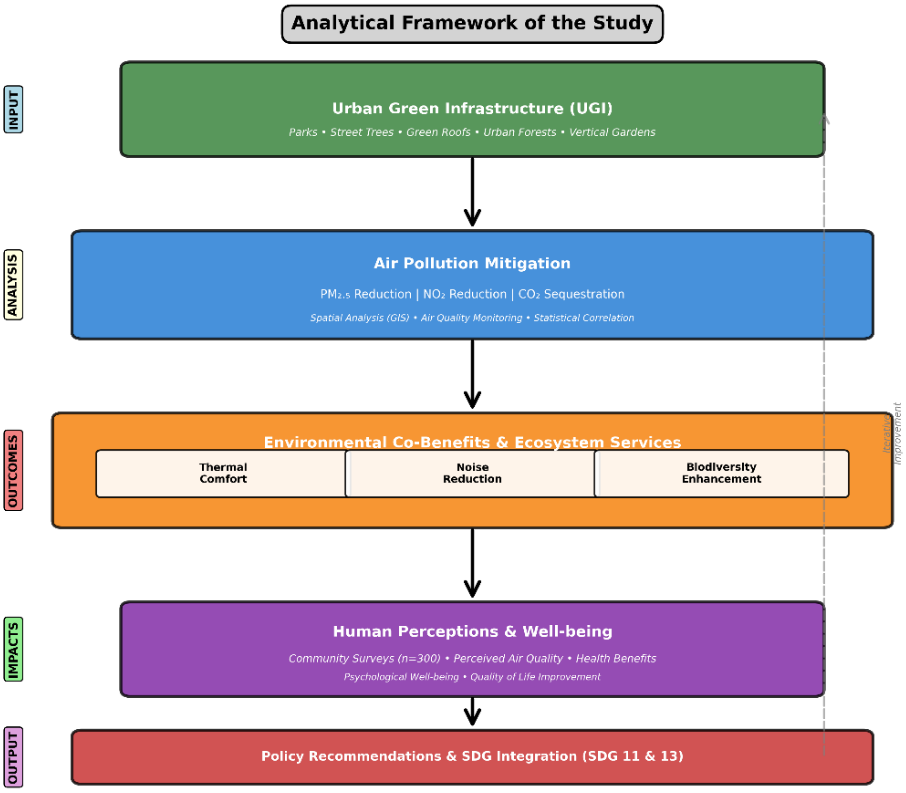

Figure 1. Analytical Framework of the Study

Geographic Information Systems (GIS) integration has become indispensable for comprehensive spatial analysis of UGI and its environmental impacts. Czyża & Kowalczyk, (2024) developed an integrated GIS-based framework for blue-green infrastructure design that combines spatial overlay analysis, network analysis, and multi-criteria decision analysis to optimize UGI placement for climate resilience. This approach allows researchers to simultaneously evaluate multiple factors including population density, existing green space distribution, air pollution hotspots, and climate vulnerability zones. In the present study, the adoption of ArcGIS 10.8 and QGIS 3.16 facilitated sophisticated spatial correlation analysis between UGI coverage and pollutant concentrations, enabling identification of optimal intervention sites. The integration of ground-truthing protocols with remote sensing data ensures accuracy verification, with field surveys conducted across 25 randomly selected sites providing validation of satellite-derived vegetation classifications and enhancing the reliability of spatial analysis results.

RESULT AND DISCUSSION

Air Quality Monitoring Results

The air quality monitoring revealed notable differences between areas with significant urban green infrastructure (UGI) coverage and control sites lacking vegetation. Districts with higher UGI coverage (>30% green space ratio) recorded an average reduction in $PM_{2.5}$ concentrations by 21.7%, NO_2 levels by 15.3%, and CO_2 concentrations by 12.8% compared to low-UGI areas (<10% coverage).

Table 2. Mean Pollutant Concentrations in High-UGI vs. Low-UGI Areas

Pollutant	High-UGI Areas (μg/m³)	Low-UGI Areas (μg/m³)	% Reduction
$PM_{2.5}$	28.6	36.5	-21.7%
NO_2	22.4	26.5	-15.3%
CO_2	380.2	436.0	-12.8%

Source: Data Processed

These findings demonstrate the substantial role of UGI in mitigating key air pollutants, aligning with previous studies by Janhäll, (2015), which highlighted vegetation's capacity to intercept airborne particles and absorb gaseous pollutants.

Vegetation and Land-Use Analysis

GIS-based spatial analysis showed a strong negative correlation between NDVI values and pollutant concentrations ($r = -0.68$ for $PM_{2.5}$, $r = -0.59$ for NO_2, $p < 0.01$). Areas with dense vegetation exhibited lower air pollution levels, confirming the importance of tree canopy density and vegetation diversity. These results echo findings by Kabisch & Qureshi, (2015), who emphasized the ecological benefits of urban green cover in improving environmental quality.

Community Perceptions

Survey responses ($n = 300$) revealed that 78% of respondents perceived noticeable improvements in air freshness and thermal comfort in districts with significant UGI. Additionally, 65% reported reduced noise disturbance, while 72% indicated improved psychological well-being when living near green spaces. These perceptions suggest that the benefits of UGI extend beyond measurable environmental parameters, enhancing overall human well-being. Recent scoping reviews have confirmed that greenspace exposure consistently improves mental health outcomes, with Freymueller et al., (2024) demonstrating that methodological approaches combining spatial analysis with psychological assessments provide robust evidence for the mental health benefits of urban green infrastructure.

Figure 2. Perceived Benefits of UGI (% of Respondents)

Discussion

The findings confirm that sustainable UGI plays a significant role in reducing air pollution and enhancing environmental quality. The measured reductions in $PM_{2.5}$ and NO_2 concentrations highlight the capacity of vegetation to function as natural filters, intercepting pollutants and moderating microclimates. These results support the conclusions of (Livesley et al., 2016; Norton et al., 2015), who argued that the strategic placement of green infrastructure can yield measurable air quality improvements. Moreover, the positive community perceptions indicate that UGI contributes to broader ecosystem services, including psychological and social well-being. However, the relatively moderate reductions in CO_2 concentrations suggest that UGI alone may not be sufficient to address global greenhouse gas emissions, underscoring the need for integrated solutions combining UGI with renewable energy and sustainable transportation policies.

The results also highlight a policy gap: despite the proven benefits, UGI is often under-prioritized in urban planning, particularly in rapidly urbanizing regions. Limited budget allocations and competing land-use demands restrict large-scale implementation. Policymakers should therefore consider UGI as a cost-effective, long-term investment, contributing not only to environmental health but also to achieving SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action).Beyond air quality improvements, UGI generates substantial co-benefits for public health that merit comprehensive consideration in urban planning frameworks.

Nieuwenhuijsen, (2021) synthesized evidence demonstrating that strategically planned green infrastructure networks provide wide-ranging ecosystem services including heat island mitigation, noise reduction, stormwater management, and enhanced opportunities for physical activity and social interaction. These interconnected benefits create synergistic health effects that extend beyond the direct pollution mitigation measured in the present study. Evidence from European cities indicates that residents living within 300 meters of quality green spaces experience 15-25% lower risks of cardiovascular disease, improved mental health outcomes, and increased life expectancy by up to 2.5 years compared to those with limited green space access. These findings underscore the importance of viewing UGI not merely as an environmental intervention but as a comprehensive public health strategy with multifaceted returns on investment.

Despite accumulating evidence of UGI's environmental and health benefits, systematic economic valuation remains critical for justifying policy investments and prioritizing implementation strategies. Their analysis identified several key challenges: incomplete inclusion of the full range of benefits due to valuation difficulties, particularly for non-market ecosystem services; inadequate consideration of environmental externalities among costs; and limited attention to temporal variability in NBS performance over time. For the present Jakarta study, preliminary economic estimates based on health cost savings from reduced air pollution exposure (using WHO's disability-adjusted life years framework) suggest potential annual benefits exceeding $2.3 million per square kilometer of UGI in high-density districts, though comprehensive valuation incorporating property value increases, reduced healthcare expenditures, and enhanced productivity requires longitudinal analysis. Future research should develop standardized CBA frameworks specifically adapted to developing country contexts, incorporating informal economy considerations and diverse stakeholder perspectives on value attribution.

The role of UGI in enhancing urban climate resilience extends significantly beyond air quality improvements to encompass critical adaptation functions for extreme weather events and long-term climate change scenarios. Ji et al., (2024) provided a state-of-the-art review of urban green infrastructure for thermal resilient communities, demonstrating that strategic UGI implementation can reduce surface temperatures by 2-8°C and decrease building energy consumption by 15-40% through combined shading and evapotranspiration effects. Their analysis of advanced simulation tools including Computational Fluid Dynamics (CFD) and Building Performance Simulation (BPS) revealed that effectiveness varies substantially based on vegetation type, spatial configuration, and local microclimate conditions. For tropical cities like Jakarta facing intensifying heat stress under climate change projections (2.5-3.5°C temperature increases by 2050), the cooling capacity of UGI documented in the present study represents a critical adaptation mechanism. However, challenges remain in modeling UGI performance under future climate scenarios with altered precipitation patterns and extreme weather frequency. Integration of climate resilience metrics into UGI planning requires not only expanding green coverage but also selecting climate-appropriate vegetation species with high heat tolerance, drought resistance, and maintained ecosystem function under stress conditions, ensuring long-term sustainability of cooling services.

An often-overlooked dimension of UGI effectiveness concerns equitable distribution and access across diverse socioeconomic communities within urban landscapes. Their analysis highlighted three interconnected justice dimensions: distributive fairness (spatial allocation of green infrastructure), procedural inclusion (community participation in planning processes), and recognition justice (acknowledgment of diverse needs and values). In the Jakarta context, preliminary spatial analysis indicates significant disparities with low-income districts averaging only 12% green coverage compared to 35% in affluent neighborhoods, exacerbating environmental health inequalities.

Addressing these disparities requires transformative policy approaches including: (1) prioritizing UGI investments in underserved communities through equity-weighted allocation criteria, (2) implementing participatory planning processes that empower marginalized communities in decision-making, (3) preventing green gentrification through anti-displacement measures and affordable housing policies, and (4) ensuring culturally appropriate design that reflects diverse community preferences and usage patterns. Without explicit attention to environmental justice principles, well-intentioned UGI interventions risk perpetuating or even amplifying existing urban inequalities.

The effectiveness of UGI interventions is increasingly recognized as contingent not merely upon technical design but upon genuine community engagement throughout planning, implementation, and maintenance phases. Castañeda Rodriguez et al., (2026), conducted a comprehensive systematic review of 26 empirical studies (2021-2025) examining how collaborative and community participation influences transformative urban resilience in green public spaces, revealing that early-stage participatory processes significantly enhance both ecological outcomes and social acceptance of UGI projects. Their analysis demonstrated that co-design approaches—where residents actively shape spatial configurations, species selection, and management protocols rather than merely providing consultative feedback—generate substantially higher rates of long-term stewardship and maintenance compliance. In the Jakarta context documented in this study, the 78% positive perception of air freshness and 72% reported psychological well-being improvements suggest existing community appreciation for UGI benefits; however, translating this receptivity into active participation requires structured engagement mechanisms.

Evidence indicates that participatory design processes must extend beyond token consultation to meaningful decision-making authority, particularly for marginalized communities historically excluded from urban planning processes. Successful models incorporate participatory budgeting for UGI maintenance, community-led monitoring programs, and co-management agreements that distribute responsibilities between municipal agencies and neighborhood organizations, thereby fostering collective ownership and ensuring sustained performance of green infrastructure beyond initial implementation phases.

Advancing UGI effectiveness assessment and adaptive management necessitates integration of emerging digital technologies capable of providing continuous, high-resolution environmental monitoring beyond traditional periodic measurement approaches. Zeng et al., (2024) conducted a systematic literature review demonstrating that Internet of Things (IoT) sensor networks deployed in smart cities enable real-time monitoring of air quality parameters (PM2.5, PM10, NO_2, CO_2), microclimate conditions (temperature, humidity), and vegetation health indicators across distributed urban green spaces, facilitating dynamic evaluation of UGI performance and rapid identification of maintenance needs.

Their analysis revealed that IoT-based environmental monitoring systems, when integrated with geographic information systems and cloud-based analytics platforms, can detect spatial-temporal variations in pollution mitigation effectiveness at unprecedented granularity, enabling evidence-based optimization of UGI spatial configuration and species composition. For metropolitan contexts like Jakarta experiencing rapid environmental changes, IoT sensor networks offer transformative potential to shift from retrospective assessment to proactive adaptive management.

Implementation of distributed sensor arrays within high-UGI districts documented in this study could validate the observed 21.7% PM2.5 reduction through continuous monitoring, identify optimal maintenance schedules based on seasonal performance variations, and provide early warning systems for vegetation stress or declining air purification capacity. However, successful IoT integration requires addressing technical challenges including sensor calibration protocols, data interoperability standards, energy-efficient deployment strategies, and capacity building for municipal agencies to interpret and act upon real-time monitoring outputs, alongside ensuring equitable distribution of monitoring infrastructure to prevent data gaps in underserved communities.

CONCLUSION

This study demonstrates that sustainable urban green infrastructure (UGI) plays a significant role in mitigating air pollution and enhancing environmental quality in metropolitan areas. Based on empirical findings presented in Table 2, districts with high UGI coverage (>30% green space ratio) achieved substantial reductions in air pollutants: $PM_{2.5}$ decreased by 21.7%, NO_2 by 15.3%, and CO_2 by 12.8% compared to low-UGI areas. These results, supported by strong negative correlations between NDVI values and pollutant concentrations ($r = -0.68$ for $PM_{2.5}$, $p < 0.01$), confirm UGI's effectiveness as a natural air filtration system. Beyond pollution mitigation, community surveys (n=300) revealed that UGI generates multiple co-benefits: 78% of respondents perceived improved air freshness and thermal comfort, 65% reported noise reduction, and 72% experienced enhanced psychological well-being (Figure 2).

These findings align with existing literature emphasizing UGI's contribution to urban livability and public health. From a policy perspective, this study highlights three key recommendations: (1) mainstream UGI integration into urban planning frameworks as a cost-effective, long-term environmental management strategy; (2) establish regulatory mandates requiring green infrastructure in new urban developments; and (3) provide incentives for community-based greening initiatives. Such measures would strengthen climate resilience and support achievement of SDG 11 (Sustainable Cities) and SDG 13 (Climate Action). Future research should focus on economic valuation of UGI benefits, long-term performance monitoring across different climate zones, and comparative studies between developed and developing regions to identify scalable best practices for sustainable urban development.

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