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INDOOR ENVIRONMENTAL QUALITY (IEQ) IN MUSEUMS AND HERITAGE BUILDINGS

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ABSTRACT

Museums and heritage buildings play a vital role in preserving cultural identity and history, yet maintaining suitable Indoor Environmental Quality (IEQ) within these spaces presents significant challenges. Balancing the strict environmental needs of artifact preservation with the comfort requirements of visitors has emerged as a major concern, particularly in repurposed heritage buildings that often lack modern environmental control systems. This research aims to identify the core challenges in managing IEQ in museum and heritage building environments and to explore practical approaches for improvement. Using a qualitative methodology based on literature review and secondary data analysis, the study highlights common IEQ issues such as poor air quality, unstable temperature and humidity levels, and inadequate lighting and ventilation systems. Findings reveal that these conditions not only threaten artifact preservation but also affect visitor experience and well-being. The study also explores emerging solutions, including retrofitting strategies, integrated HVAC models, and natural, non-invasive air purification techniques. A holistic approach is emphasized, integrating energy efficiency, sustainability, and comfort to improve the functionality of heritage buildings as modern public spaces. This research underscores the importance of interdisciplinary collaboration between architecture and environmental engineering in developing sustainable, people-focused, and conservation-conscious IEQ strategies for cultural institutions.

1. Introduction

Indoor Environmental Quality (IEQ) refers to the conditions within a building that influence the health, comfort, and overall experience of its occupants. These conditions include factors such as air quality, thermal comfort, lighting, and acoustics, as explained by Abdul Mujeebu,

(2019) and Petty, (2021). In the context of museums, IEQ plays a dual role. It affects the satisfaction and well-being of visitors while also being essential for the preservation of sensitive artifacts and historical materials. This balance is particularly challenging to maintain in heritage buildings, which often lack modern environmental control systems. Piasecki et al., (2020) emphasized that retrofitted historical buildings must carefully address thermal conditions, ventilation, lighting, and acoustics to meet appropriate environmental standards. Additionally, museums constantly face the challenge of optimizing energy efficiency without compromising either artifact protection or visitor comfort. Dabanlis et al., (2023) highlighted the difficulty of balancing these sometimes-conflicting requirements in museum environments. The complexity is further increased by the global variation in climate control practices and regulatory frameworks, as observed by Elkadi et al., (2021). Due to the close connection between architectural preservation, environmental management, and user experience, maintaining appropriate IEQ in museums requires a comprehensive and multidisciplinary approach that prioritizes both conservation and human comfort.

Considering the importance of maintaining appropriate indoor environmental conditions, it is essential to understand the unique characteristics of museums and heritage buildings where IEQ must be carefully addressed. Museums are institutions dedicated to the collection, preservation, and exhibition of culturally significant objects, which play a central role in supporting education, cultural identity, and academic research. Hens, (2019) described museums as buildings that store, preserve, and display collections of artifacts. Similarly, Konsa and Jeeser (2019) emphasized that museums serve as memory institutions that safeguard culturally valuable materials and help to shape social and historical understanding. In many cases, museums are located within heritage buildings, which are structures recognized for their historical, architectural, or cultural significance. Chung (2007) explained that such historic buildings can themselves be regarded as part of the museum collection, offering educational and experiential value through their original settings.

Poor indoor environmental quality (IEQ) poses significant risks to museums in Malaysia, as fluctuations in temperature, humidity, and air pollutants can accelerate the deterioration of artifacts while also threatening the integrity of heritage building structures (D. Ilieș et al., 2021). For example, the Pahang State Museum highlights the importance of adhering to preservation guidelines that safeguard both architectural authenticity and cultural continuity (Zulkifli & Bakar, 2020). Ensuring stable IEQ is therefore critical, as it directly influences the dual responsibility of museums to conserve artifacts and maintain the architectural fabric of heritage buildings.

Research on IEQ in Malaysian museums and heritage buildings remains relatively limited, although several studies conducted more than five years ago have addressed this issue. Several studies have begun to shed light on air quality concerns, thermal comfort, and potential environmental risks in these culturally significant spaces. Dzullkifli et al. (2018) examined the indoor environment at the Melaka Sultanate Palace Museum and the History and Ethnography Museum, revealing that pollutant levels such as nitrogen dioxide, sulfur dioxide, and particulate matter were influenced by proximity to nearby roadways. Their findings raised concerns about whether current indoor conditions are suitable for both human health and artifact preservation. Similarly, Sulaiman, Kamaruzzaman, and Yau (2019) observed that, although temperature and

carbon dioxide levels in selected museum galleries generally met recommended thresholds, poor ventilation and ineffective air conditioning layouts hindered overall air quality performance. Prihatmanti and Bahauddin (2014), in a study on adaptively reused heritage buildings in George Town, Penang, reported high humidity, dampness stains, and microbial contamination, largely due to inappropriate adaptive reuse strategies and inconsistent maintenance practices. These conditions not only affect the longevity of heritage structures but also impact occupant well-being. From a user perspective, Zulkifli, Goh, and Kamaruzzaman (2014) highlighted staff and visitor discomfort in Malaysian museums, where symptoms of sick building syndrome were associated with unsatisfactory indoor conditions such as poor thermal control, lighting, and air quality. Adding to the urgency, Hanapi and Mohd Din (2018) found that concentrations of airborne particulate matter in selected museum galleries exceeded national safety standards, posing direct risks to both cultural artifacts and human health. Further assessments by Dzullkifli et al. (2018) used a risk categorization method to evaluate 24 museum buildings across Malaysia, identifying several with medium environmental risk levels, thereby emphasizing the need for targeted intervention. Collectively, these studies indicate that while awareness of IEQ issues in Malaysian museums is growing, there remains a significant gap in comprehensive, integrated strategies that address both environmental quality and heritage conservation goals within these unique public spaces.

This study explores the foundational understanding of IEQ in museums and heritage buildings, with a particular focus on the Malaysian context. IEQ includes key environmental factors such as air quality, thermal comfort, lighting, and ventilation, all of which are essential for both artifact preservation and visitor comfort. Museums, especially those housed in heritage buildings, often struggle to maintain adequate IEQ due to outdated infrastructure and the absence of modern environmental control systems. The literature reviewed reveals persistent challenges such as high humidity, poor air circulation, and pollutant accumulation, which negatively impact both human health and cultural preservation. Malaysian studies further highlight issues related to poor adaptive reuse practices, maintenance shortcomings, and the health symptoms experienced by occupants. As a preliminary step, this research maps out the surface-level challenges and conditions that shape IEQ in these unique environments before advancing to a deeper investigation of potential improvement strategies. By emphasizing this foundation, the study supports the need for holistic, sustainable, and interdisciplinary approaches that address the dual function of heritage museums as both public spaces and conservation sites.

2. Methodology

This study employed a qualitative research approach using a narrative literature review to examine IEQ in museums and heritage buildings, focusing on challenges, impacts, and strategies for improvement. A total of 22 journal articles, conference papers, and technical reports published between 2010 and 2024 were reviewed, retrieved using keywords such as *"Indoor Environmental Quality," "museums," "heritage buildings,"* and *"Malaysia."* The search was refined with Boolean operators, while inclusion criteria emphasized relevance to cultural heritage and tropical contexts, and exclusion criteria removed duplicates, non-English works, and unrelated studies. The selected articles were analyzed using **Atlas.ti 23**, which facilitated coding and thematic analysis, leading to the identification of key themes including

air quality management, thermal comfort, building adaptation challenges, conservation risks, and occupant well-being.

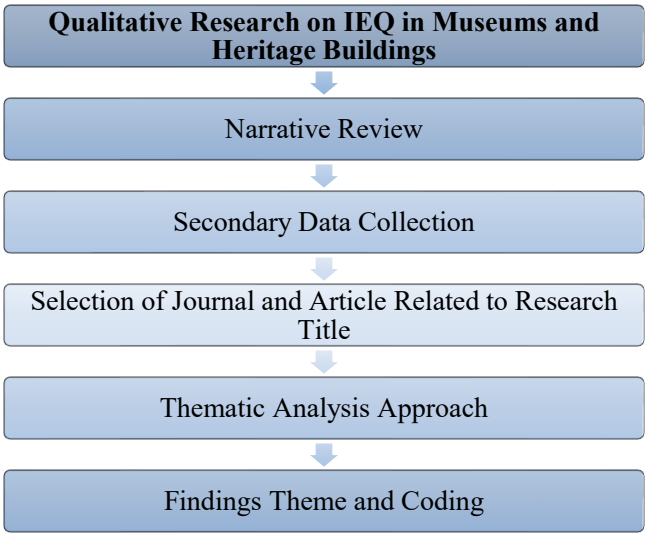

Figure 1. Research Methodology Flowchart

3. Results

3.1 Conflicts Between Artifact Conservation and Visitor Comfort Due to Poor IEQ Management

Managing IEQ in museums and heritage buildings presents persistent conflicts between the conservation needs of artifacts and the comfort expectations of visitors. One of the most fundamental challenges is the requirement for different optimal conditions; while artifacts demand highly stable temperature and humidity levels, visitors prefer dynamic airflow and thermal comfort, creating a direct conflict in environmental control priorities (Cirrincione et al., 2024; Elkadi et al., 2021). Many heritage museums further complicate this balance as their architectural limitations make it difficult to install modern HVAC systems, impeding efforts to regulate indoor climate effectively (Cirrincione et al., 2024; Efthymiou et al., 2021). As a result, thermal environments in these spaces may be cold, humid, or poorly ventilated, contributing to significant visitor discomfort (Efthymiou et al., 2021; Schito et al., 2020). Additionally, human activity within museums introduces further complications; visitors emit heat, CO_2, moisture, and odors, all of which alter the microclimate and accelerate artifact deterioration, especially under poor ventilation (Silva & Henriques, 2021; Ilieș et al., 2021). Attempts to enhance energy efficiency by reducing HVAC usage often worsen air quality, undermining both human health and preservation goals (Dabanlis et al., 2023; Schito et al., 2020). Moreover, the presence of airborne pollutants like VOCs, particulate matter, and biological contaminants such as mold poses health risks to staff and visitors while also damaging sensitive collections (Ilieș et al., 2021; Ilieș et al., 2022). The lack of unified standards and guidelines exacerbates these issues, leading to inconsistent environmental management practices across institutions (Elkadi et al., 2021). Finally, retrofitting heritage buildings to simultaneously meet the needs of conservation and visitor comfort is complex, with compromises in one area often leading to deterioration in the other (Efthymiou et al., 2021; Cirrincione et al., 2024). These intersecting conflicts

underscore the need for integrative IEQ strategies that respect both preservation requirements and human-centered design. Figure 2 illustrates the summary of key areas of conflict between conservation needs and visitor comfort in heritage museum environments.

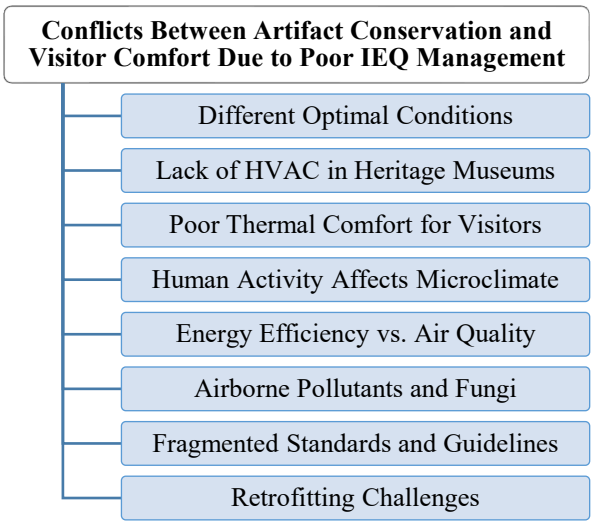

Figure 2. Key Areas of Conflict Between Conservation Needs and Visitor Comfort in heritage Museum Environments

3.2 Key Issues of IEQ in Museums

The management of IEQ in museums presents significant challenges due to the diverse and often conflicting requirements of artifact conservation and visitor comfort. Museums are expected to maintain controlled microclimates that are essential for preserving delicate and irreplaceable artifacts. At the same time, they must ensure that the indoor environment supports thermal, acoustic, and visual comfort for visitors and staff. These dual objectives are frequently incompatible, particularly within heritage buildings where structural and historical constraints limit the feasibility of environmental modifications (Cirrincione et al., 2024; Elkadi et al., 2021; Pisello et al., 2017). In many cases, IEQ components such as air quality, lighting, temperature, and sound levels are addressed in isolation, which leads to fragmented and often ineffective solutions (Sulaiman et al., 2011; Elkadi et al., 2021). Compounding this issue is the absence or limitation of HVAC systems in numerous heritage museums. These buildings often lack the physical capacity or architectural compatibility to support the installation of modern climate control technologies, resulting in fluctuating indoor conditions that are unsuitable for both artifacts and occupants (Cirrincione et al., 2024; Efthymiou et al., 2021).

Indoor air quality remains a particularly pressing issue in museum environments. Elevated concentrations of Volatile Organic Compounds (VOCs), Carbon Dioxide (CO_2), particulate matter, and formaldehyde have been documented, posing health risks to visitors and contributing to the accelerated deterioration of collections (Ilieș et al., 2021; Chiantore and Poli, 2021; Prihatmanti and Bahauddin, 2014; Leyva et al., 2016). Furthermore, insufficient ventilation combined with high humidity levels creates ideal conditions for fungal and microbial growth. These biological contaminants not only compromise the integrity of artifacts but also pose significant respiratory risks to staff and the visiting public (Ilieș et al., 2022; Ilieș

et al., 2021). Maintaining stable thermal conditions is also a challenge, particularly in older museum buildings where temperature and humidity control systems are inadequate or entirely lacking (Efthymiou et al., 2021; Pisello et al., 2017; Piasecki et al., 2020). Museums in developing regions often struggle with these challenges due to limited funding and technological access, which restrict their ability to meet international IEQ standards (Elkadi et al., 2021). In addition, poor maintenance practices and inappropriate adaptive reuse of heritage buildings have been linked to persistent environmental degradation (Prihatmanti and Bahauddin, 2014; Piasecki et al., 2020). Display materials used within exhibition spaces may also release harmful emissions, such as VOCs, which threaten the longevity of museum collections (Chiantore and Poli, 2021). Efforts to reduce energy consumption often compromise air quality and climate stability, creating difficult trade-offs between sustainability objectives and conservation goals (Dabanlis et al., 2023; Schito et al., 2020). Finally, inconsistent regulatory frameworks and overwhelming volumes of environmental data pose additional challenges for museum staff attempting to implement effective and coordinated environmental management strategies (Elkadi et al., 2021; Leyva et al., 2016). The researcher has summarized the key issues in managing IEQ in museums and heritage buildings, as shown in Figure 3.

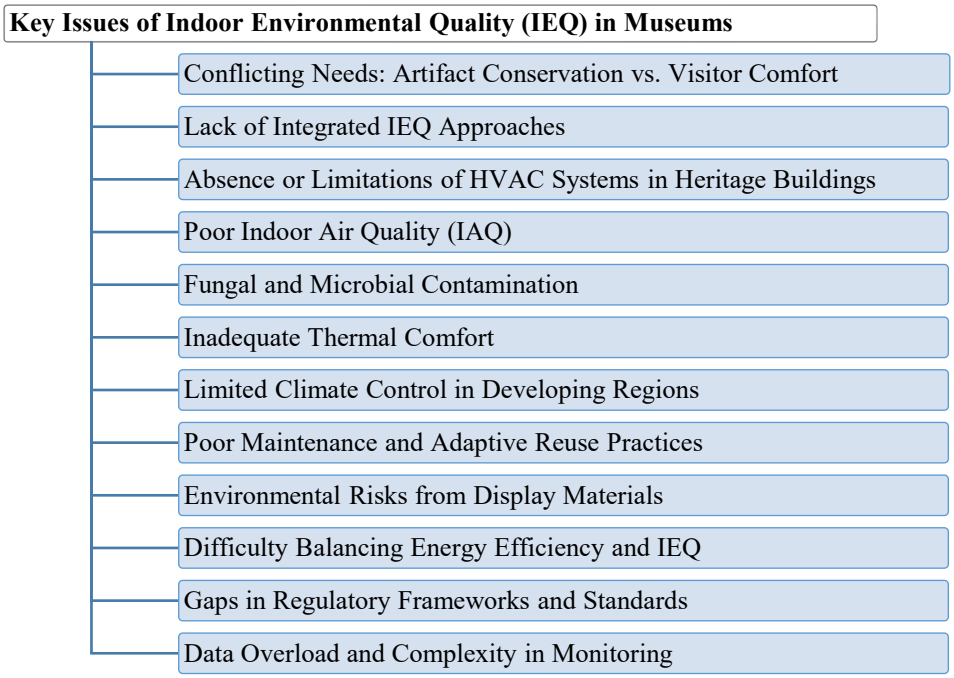

Figure 3. Summary of Key Issues in Managing IEQ in Museums and Heritage Buildings
Source: Author

3.3 Advantages of IEQ Studies in Museums and Heritage Buildings

Even though many issues and conflicts related to IEQ in heritage buildings have been identified by researchers in previous studies, further research on this topic offers significant advantages. IEQ studies help maintain stable environmental parameters such as temperature, humidity, and pollutant levels to preserve sensitive collections and historical artifacts (Sulaiman et al., 2011; Elkadi et al., 2021; Badea et al., 2022). They also improve thermal, visual, and acoustic comfort

for both visitors and staff, enhancing overall wellbeing and experience (Sulaiman et al., 2011; Karaca, 2022; Elkadi et al., 2021). In addition, IEQ monitoring enables early detection of risks such as mold, VOCs, and pollutants that threaten both health and preservation (Ilieș et al., 2022; Chiantore & Poli, 2021; Leyva et al., 2016). These studies support sustainable and energy-efficient operations by informing retrofitting and climate control strategies (Dabanlis et al., 2023; Badea et al., 2022), and they serve as a foundation for holistic environmental management in aging museum infrastructure (Willems et al., 2020; Diaz et al., 2021). Moreover, they guide the development of regulatory and design standards, particularly in regions without formal climate guidelines for museums (Elkadi et al., 2021; Fisk et al., 2011), and promote staff productivity and health in museum workspaces (Brager, 2013; Karaca, 2022; Mujeebu, 2019). Maintaining good IEQ also adds economic and strategic value by reducing maintenance costs and boosting tourism through improved visitor satisfaction (Fisk et al., 2011; Mujeebu, 2019; Brager, 2013). Furthermore, these studies drive technological innovation with tools like IoT-based monitoring systems (Badea et al., 2022; Zhang et al., 2023) and foster interdisciplinary collaboration among experts in heritage conservation, environmental engineering, and architecture (Willems et al., 2020; Elkadi et al., 2021). Despite the challenges and conflicts associated with managing Indoor Environmental Quality (IEQ) in heritage buildings, further research in this area provides significant advantages such as preserving sensitive artifacts, improving comfort for visitors and staff, enabling early risk detection, supporting energy-efficient operations, informing design and regulatory standards, and fostering innovation and interdisciplinary collaboration. The researcher has summarized these key benefits in Figure 4.

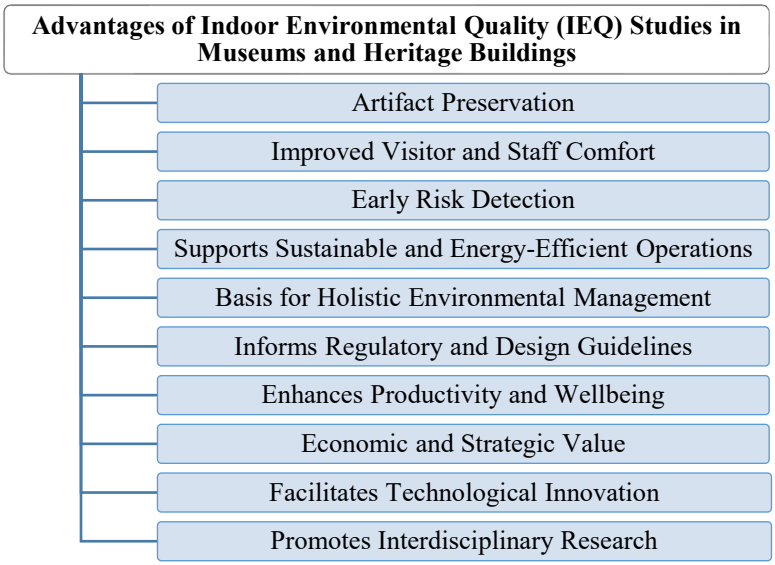

Figure 4. Summary of the Advantages of IEQ Studies in Museums and Heritage Buildings
Source: Author

4. Discussion

The findings of this research indicate that managing IEQ in museums and heritage buildings involves a persistent conflict between the environmental needs of artifact conservation and the comfort expectations of human occupants. The preservation of sensitive cultural objects requires tightly controlled conditions, such as stable temperature and humidity levels, as well as minimal exposure to pollutants. In contrast, visitors and staff require dynamic air circulation, thermal comfort, and adequate lighting to ensure a positive experience. These differing requirements are often incompatible, particularly in heritage buildings that were not originally designed to accommodate modern environmental systems. For instance, reducing HVAC usage to conserve energy may lower operational costs, but it can also lead to thermal discomfort and air stagnation. These outcomes contribute to the growth of mold and airborne pollutants, which not only affect the integrity of collections but also compromise public health. These overlapping challenges highlight the necessity of adopting IEQ strategies that are both conservation-aware and human-centered, as noted by Cirrincione et al. (2024) and Elkadi et al. (2021).

In response to the complex IEQ issues identified in this study, recent research has introduced a range of practical approaches as shown in Figure 5, that improve environmental conditions in museums and heritage buildings while preserving their historical and cultural integrity. One such approach involves the use of a holistic IEQ-energy assessment framework, which integrates building conservation with modern performance metrics to support informed retrofit strategies (Divolis et al., 2024). Retrofitting heritage masonry with mineral-based internal insulation has also proven effective in enhancing thermal comfort and reducing mold growth (Piasecki et al., 2020; 2021). In addition, non-invasive mechanical ventilation systems, such as hidden ductwork with heat recovery and airflow dampers, have shown promising results in improving air quality without altering the architectural fabric (Hamid et al., 2020). Emerging technologies, such as digital twin systems paired with adaptive HVAC control, use real-time sensor feedback and computational modeling to adjust ventilation settings, achieving energy savings while maintaining appropriate indoor air quality (Zhang et al., 2023).

Other innovative solutions include the use of essential oils to inhibit fungal contamination in museum environments, providing a natural and low-impact alternative to chemical treatments (Ilieș et al., 2022). Environmental risk management tools have been developed to assess threats and support low-impact operational responses tailored to the unique needs of heritage sites (Lucchi, 2020). Systematic ventilation planning based on international standards, such as EN 16883:2017, helps align ventilation system types with the heritage value and physical characteristics of buildings (Rieser et al., 2021). Research also supports the development of pollutant monitoring and microclimate assessment protocols that guide preventive interventions (Efthymiou et al., 2021; Sciurpi et al., 2022). By integrating quantitative sensor data with qualitative insights into user experience, combined IEQ research enables more informed, human-centered environmental design strategies (Willems et al., 2020). Furthermore, guidance for sustainable renovation by local occupants (Senior et al., 2021) and climate-specific retrofitting solutions (Elkadi et al., 2021) ensure that improvements are socially inclusive and environmentally responsive. Collectively, these approaches represent a shift toward integrated, interdisciplinary strategies that enhance both the functionality and sustainability of museums and heritage buildings.

5. Conclusion

This study has examined the complex challenges of managing IEQ in museums and heritage buildings, focusing on the persistent conflict between the preservation of sensitive artifacts and the provision of comfort for visitors within the limitations of historical architecture. Various improvement strategies, such as adaptive ventilation systems, retrofitting with internal insulation, and integrated monitoring protocols, have demonstrated potential for addressing these challenges. However, their implementation remains inconsistent and is often hindered by architectural limitations, financial constraints, and the absence of supportive regulatory frameworks. Therefore, further research is necessary to develop comprehensive, cost-effective, and conservation-sensitive IEQ strategies that are specifically designed for heritage contexts. One significant gap identified is the lack of integrated approaches that consider all aspects of IEQ, including thermal comfort, air quality, lighting, and acoustics, in a coordinated manner. Another gap lies in the absence of climate-specific guidelines that align environmental management practices with local weather conditions, visitor behavior, and the cultural value of the buildings. Addressing these gaps through interdisciplinary collaboration and context-sensitive innovation is essential to safeguard the long-term integrity of heritage buildings and artifacts while enhancing the health, well-being, and experience of visitors and museum staff.

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