【研究報告】

Numerical Simulation of the Environmental Conditions in Tainan Confucius Temple as a Means of Planning Preventive Conservation Strategies

溼熱氣候下文化資產預防性保存：以國定古蹟臺南孔廟為例

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Abstract

This study takes the Taiwan Confucius Temple in Tainan City as an example to evaluate preventive conservation for Taiwanese cultural assets in a hot and humid climate. We principally used microclimate monitoring data and computational fluid dynamics simulation to analyze the overall environment and identify problem areas. The results indicated that the ritual implement and musical instrument storerooms were problematic. The latter had the highest relative humidity due to a mango tree located at the rear of the building with a canopy stretching 4–6 meters across the roof, blocking the sunlight during the day and preventing any reduction in relative humidity. This storeroom includes the original calligraphic wall panels and the central beam of the Minglun Hall. We propose measures to improve the current environment without the necessity of modifying the building materials or structures. First, this study suggests either changing the display items or relocating the exhibition area, and transplanting or pruning the mango tree. Second, dehumidification or ventilation equipment should be placed not only in the musical instrument storeroom but also in the Chung Sheng Shrine and Dacheng Hall at night during the hot season, and in the ritual implement storeroom in the day during the cold season. We suggest this will improve the environmental problems.

Keywords: Historic Building, Preventive Conservation, Computational Fluid Dynamics, Natural Ventilation, Micro Climate

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摘要

本文以臺南孔廟為例，探討溼熱氣候下臺灣文化資產的預防性保存，主要運用微氣候監測數據，以及計算流體力學（Computational Fluid Dynamics, CFD）模擬，分析個案的整體環境，並且指認問題區域。從監測與模擬結果可知，禮器庫、樂器庫為主要的問題區域，其中樂器庫溼度最高，且後方芒果樹白日遮蔽屋頂，使陽光照射受阻，室內溼度偏高，而且該區展示品為明倫堂原壁內板雕及中樑，因此，在不改變建材或格局的條件下，提出現況環境改善措施，首先建議更改該區展品內容，或變更展區，以及移溼或通風設備；禮器庫於涼季白天時段積極採用除溼設備，改善上述時段的環境問題。

關鍵詞：歷史性建築、預防性保存、計算流體力學、自然通風、微氣候

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1. INTRODUCTION

Climate change has become a critical issue worldwide. In 1992, the "United Nations Framework Convention on Climate Change" focused attention on this issue. In 2015, the Paris Agreement further agreed goals backed by law that require mitigating or coping with climate change. Climate change will enlarge existing risks and produce new risks to nature and humans. In response to abnormal climate conditions, countries have turned their attention to preventive conservation of cultural heritage and initiated a series of plans and actions. From 2004 to 2007, the Noah's Ark Project of the Sixth Framework Program supported by the European Commission applied micro-scale analysis to cultural heritage and subsequently countermeasures were implemented. The Smart Monitoring of Historic Structures (SMOOHS) of the Seventh Framework Program project (2008–2010) and the Climate Culture project (2009–2014) had the same objective of preventing future climate and environmental changes from affecting cultural heritage on both the macro- and micro-sale. Both projects were micro-scale analysis. SMOOHS focused on the development of smart monitoring systems using wireless networks of miniature, robust sensors for minimally invasive installation at historic structure, and a platform providing smart data processing of indoor microclimate monitoring data. Climate Culture mainly assessed the impact of climate change on European cultural heritage, historic buildings, and internal collections to identify potential hazards and develop strategies to mitigate the effects of climate change. Some of these studies were done by numerical simulation software WUFI PLUS to simulate and evaluate the temperature and relative humidity of the indoor environment.

Similarly, the Tokyo National Research Institute for Cultural Properties has conducted numerous studies with the purpose of planning preventive conservation efforts, especially regarding outdoor cultural properties. They have adopted methods such as long-term monitoring or surveying, modeling experiments, and Computational Fluid Dynamics (CFD) simulation analysis to analyze the relationship between objects and the environment and to propose control strategies and improvement methods. Their research results have mainly yielded repair strategies.

In recent years, research on preservation issues (Camuffo, 2014; D'Agostino, Congedo, & Cataldo, 2013; Ogura, Hokoi, Li, Ishizaki, & Miura, 2009; Tokyo National Research Institute for Cultural Propertie, 2011) mostly used long-term observations supplemented by numerical simulations to identify issues and propose potential solutions. The objective of the long-term measurements was to collect standardized data which was evaluated at regular intervals to identify issues and to propose adequate measures for prevention. Therefore, based on this trend, this current work uses the two methods of analysis of monitoring data and numerical simulation.

Taiwan has a hot and humid climate,

which is not ideal for preserving traditional buildings. If Taiwan does not act quickly, preservation and repair work will be even more costly than it is now. Compared with the achievements of some other countries in recent years, Taiwan's relevant actions and research on climate and preservation are still in their infancy. Preventive conservation in Taiwan requires further research and implementation. This paper focuses on the micro-scale analysis of the effects of climate change and describes the initial steps in this kind of research undertaken internationally. It applies the current state of the environment as the basis for further research in the future. First, an important cultural property in Taiwan is selected and then basic environmental monitoring data were collected. These data were subsequently used to verify whether the CFD model is capable of adequately simulating the environment and identifying problem areas and make recommendations for improvement.

2. STUDY AREA

The Tainan Confucius Temple (TCT) was the first Confucius temple in Taiwan. Located in Tainan City in southern Taiwan, it was constructed in 1665. At that time, it was the only school that Taiwanese children could attend, and thus it is also referred to as the first school in Taiwan. In 1684, the TCT was expanded to its current scale. Because it is an important cultural property of Taiwan, the government has declared it a national heritage site. Because of its high cultural value, this study used it as an example on which to base a discussion concerning preventive conservation of a cultural asset located in an urban environment among a dense cluster of modern buildings. The simulation area encompassed a circle with a radius of 500 m with the temple at the center, covering the TCT buildings, surrounding buildings, a plantation, and a water pool (Figs 1 and 2).

Fig 3 shows the spatial layout of the TCT including Dacheng Hall (A), East Wing (B), West Wing (C), Ritual Implements Store-

Fig 1. Outdoor view of the TCT
圖 1. 臺南孔廟全景（作者攝）
Source: Photo by author

Fig 2. On entering the temple each single space faces the courtyard
圖 2. 孔廟主體建築的主要空間，開口位置皆面對中庭（蔡侑樺攝）
Source: Photo by Tsai, Yu-hua

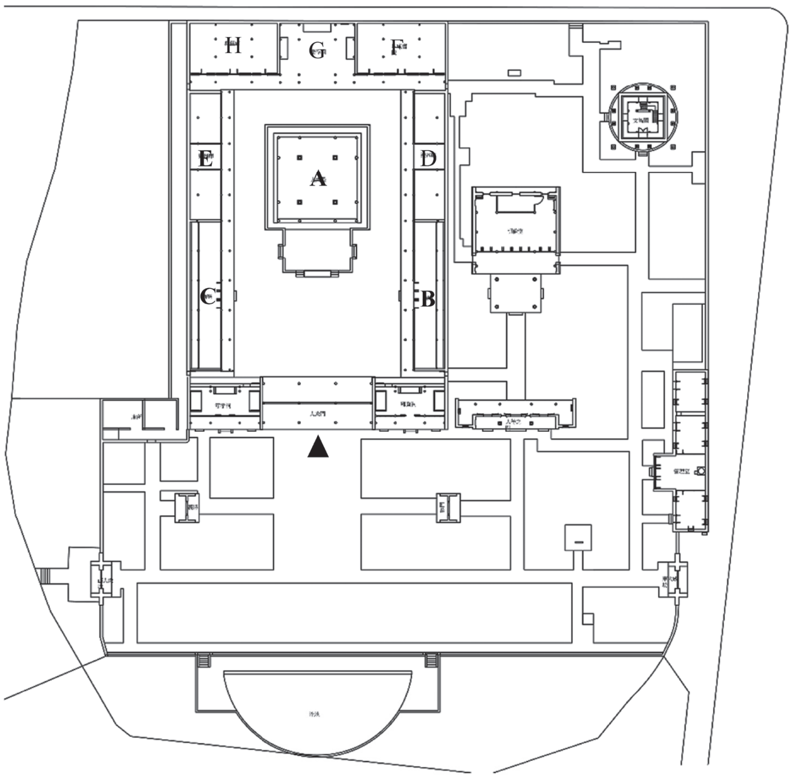

Fig 3. Plan of TCT (arrow shows the entry)
圖 3. 臺南孔廟平面圖
Source: This study

room (D), Musical Instrument Storeroom (E), Yi Cheng School (F), Chong Sheng Shrine (G), and the Library of Books Collection (H). As the library of book collection was not open it will not be discussed in this paper (Fig 3). The main openings of these spaces are located in the atrium. The wall facing the openings is the primary vertical plane and is made of wood.

The other three walls are all made of brick. Dacheng Hall, the East and West Wings, and Chong Sheng Shrine have their doors and windows open throughout the day. The Ritual Implements Storeroom, Musical Instrument Storeroom, and Yi Cheng School have their doors and windows closed at 17:30 each day. The Ritual Implements Storeroom and Musical Instrument Storeroom have small windows but, during the day, a double-panel door is kept open. Because of concern that the displays may be damaged by sunlight, the northern windows of the Musical Instrument Storeroom are kept closed all day. The inner side of the wall exhibits peeling paint. The floor is wet, generating efflorescence. In addition, the northwest side of the external wall of the Musical Instrument Storeroom leaks, and moss grows on the moist wall. A mango tree grows here; it branches covering 1/4 of the roof of the Musical Instrument Storeroom. Regarding the external side of the northern wall, large areas of paint have peeled off, and moss and fungi prosper. Dacheng Hall has an elevated roof, and its doors and windows are open throughout the day. Yi Cheng School has two double-panel doors and one single-panel door open during the day. Chong sheng Shrine is an open space, so it is easily influenced by the external climate. Its floor is severely weathered and peeled.

3. MATERIALS AND METHODS

3.1 CFD model

Because the TCT is located amidst urban architecture, the CFD model we constructed focused on block and scale. The depiction of the TCT itself included a detailed model of its indoor and outdoor spaces. Because the slope of the roof would affect the simulation results, it was portrayed in detail. The existing plantation was surveyed, and the survey documented the species and height of the trees, as well as the width of the crowns. These survey results were used in the CFD model to reconstruct the plantation and to simulate the influence of the plantation on the surrounding environment.

3.2 CFD simulation

CFD has been developed into a powerful assessment tool that is especially useful for assisting with the design of architecture and cityscapes (Blocken, van der Hout, Dekkerd, & Weiler, 2015). CFD provides the designer with precise parameters with which to plan urban or residential areas to improve the wind and thermal environment in the city; around buildings; or indoors. The implementation of CFD also reduces the effect of new designed projects on the surrounding environment and decreases future energy use. General research using CFD has studied ventilation in a building or a city, pedestrian wind fields, contaminant diffusion, the urban heat island effect, and wind energy (Amorim, Rodrigues, Tavares, Valente, & Borrego, 2013; Chu, Hsu, & Hsieh, 2017; Mochida & Lun, 2008).

This study used WindPerfect DX software developed by E-Sim (Japan) for the simulation. The governing equations were solved using LES. The simulation model was 1,000 m in diameter with the TCT at the center. The entire simulation area was 2,000 × 2,000 × 450 m in dimensions with the TCT as the focused area, whose coverage was 350 × 350 m. Because the street width was 3–6 m and the height of buildings in the TCT was 4–9 m, the grid dimensions of the focused area was 1.2 × 1.2× 1.2 m. The grid density decreased gradually from the focused area outward. The total number of grids was 9,580,889. According to the latest Wind Resistance Design Specifications and Commentary of Buildings (Wind Resistant Building Design Specification and Commentary, 2014, December 3), this area is categorized as Locality A. The surface roughness is $\alpha = 0.32$. Using this value, the vertical distribution of the average velocity at the section can be calculated using Equation (1):

$$\frac{V}{V_0} = \left[\frac{Z}{Z_0}\right]^{\alpha} \tag{1}$$

V: wind speed (m/s) at height Z
Z_0:wind velocity at reference height (m/s)
Z: a certain height (m)
V_0: height of the meteorological station (m)
α: exponent value

3.3 CFD validation

Since December 2016, the Bureau of Cultural Heritage has been installing monitoring instruments in TCT, with two outdoor monitoring stations, including one comprehensive meteorological station on the top floor of the Cultural Heritage Preservation Research Center and one three-dimensional anemometer beside the water pool of the TCT. There are 16 indoor monitoring stations in total, but they were difficult to use in the CFD simulation and verification because the indoor monitoring stations do not have the exact positions indicated on the drawing . The three-dimensional anemometer beside the water pool of the TCT is closely adjacent to and surrounded by plant groups on its south and southeast sides, which makes it impossible for this three-dimensional ultrasonic anemometer to obtain the wind velocity from 0–360° wind directions. Since only relevant data from the comprehensive meteorological station can reflect the local situation, the following simulation and verification only uses it as the data source.

The on-site data collected on the hottest day during the hot season in 2017 (September 13, 2017) were used to verify the CFD model. The maximum errors for wind velocity, temperature, and relative humidity were no more than 1 m/s, 0.2 °C, and 6%, respectively. The aforementioned small gap between simulation values and observed values demonstrated that the CFD model had explanatory power.

3.4 Monitoring data and meteorological data

In this paper, the differences between the temperature, relative humidity and wind speed of the monitoring instrument and the adjacent weather station (station number: 467410, station name: Tainan Station) are compared. The comparison results are consistent with the two trends. It can be seen that the monitoring instrument data can reflect the local climate for uses as CFD simulation verification. The comparison between the two reveals that the difference between the hot season and the cool season is extremely small with regards to humidity, wind speed, and temperature. The average temperature difference between the hot season from June to September was 0.5–0.8 °C, and the average temperature difference between the cool season from December to February was 0.35 °C, the discrepancy in average relative humidity in the hot season was 3–5%, and for the cool season 6–7%. The wind speed value comparison is shown below.

The study verifies the CFD model with the measured data, thus confirming that the CFD simulation is sufficient to simulate the weather and data of the TCT in both the hot and cool season to check for indoor and outdoor environmental problems, i.e., the day-time and night-time temperatures, the relative humidity, and wind.

4. RESULTS AND DISCUSSION

Due to the fact that relevant research in Taiwan is still in its infancy, especially the lack of chemical and biological research on cultural materials, the simulation parameters in this paper are limited. In creating the simulation, only data from the following time periods could be obtained from the comprehensive meteorological station. Furthermore, the Bureau of Cultural Heritage stipulated that no change in the materials and layout of the site was permitted; the project would only identify the problem areas, and propose simple daily management and maintenance methods and protocols.

4.1 The day time in hot season

During this period, the wind mainly comes from the west. The simulation results revealed that the wind field in the courtyard between the TCT and the semicircular pond was optimal. Minglun Hall and Wenchang Pavilion were densely surrounded by trees approximately 6–7 m tall and with crowns 4–5m wide. Although the crowns were trimmed, because the trees were planted densely together, this region exhibited a large area of wind shadow (Fig 4). In the courtyard, the wind velocity at the east and west sides of the Dacheng Hall increased (Fig 5), which subsequently influenced the wind velocity inside the East and West Wings, creating an average wind velocity of 0.2–0.5 m/s indoors. The indoor wind field of the East Wing was better than that of the West Wing. The Ritual Implements Storeroom and the Musical Instrument Storeroom had small windows, and thus the indoor wind velocity was lower, approximately 0.1 m/s or slower.

The Musical Instrument Storeroom as well as both ends of the front corridor of the Storehouse of Books and Records and Yi Cheng School exhibited high relative humid-

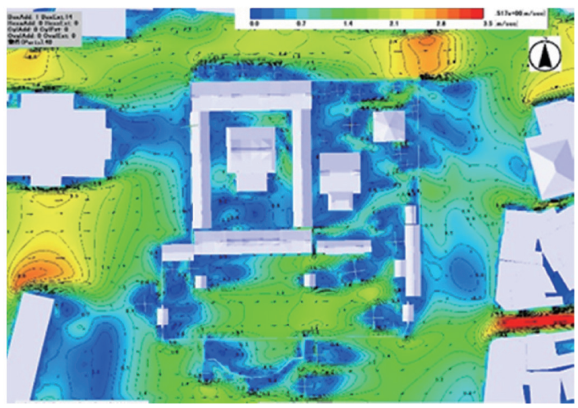

Fig 4. Wind field simulation of the outdoor space and vicinity
圖 4. 室外空間及周邊環境風場
Source: This study

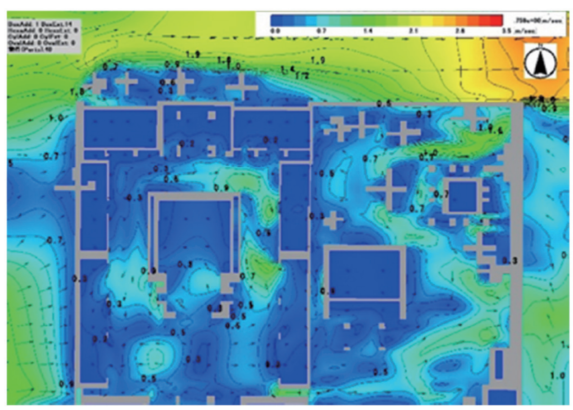

Fig 5. Indoor wind field simulation
圖 5. 室內風場
Source: This study

ity compared with other spaces (Fig 6). The average relative humidities in the front corridor ends of Yi Cheng School and the Storehouse of Books and Records were 82.7% and 85.5–86.3%, respectively. The average relative humidity of the Musical Instrument Storeroom was 84.3–86.7%. These are clearly problematic areas with poor ventilation. Because their relative humidity was over 70%, the relative humidity problem had to be addressed. We advise that the side doors at the end of the front corridor of the Storehouse of Books and Records and Yi Cheng School be opened regularly to facilitate ventilation, thereby reducing relative humidity. As for the Musical Instrument Storeroom, indoor ventilation facilities or dehumidifiers could be installed to actively dehumidify the space during the day in the hot season.

4.2 The night time in hot season

During this period, the wind was mainly from the south. The outdoor relative humidity was over 80%, and the average temperature was 28.9–29.2 °C. The indoor simulation demonstrated that the indoor average temperature was 29–30 °C, and the indoor relative humidity of all regions was higher than 83% (Fig 7). The relative humidity of the Musical Instrument Storeroom was the highest; with relative humidity in the range 92.2–99%. This is excessively high. We advise that a dehumidifier or forced ventilation equipment be installed in this place to mitigate the humidity problem at this period during this season.

4.3 The day time in cool season

The wind during this period mainly came from the north-northeast direction. The wind follows the street to the vicinity of the TCT, and the wind velocity increased. The wind velocity in the courtyard between the temple and the semicircular pond was in the range 0.6–1.0 m/s. However, within the TCT fence, the courtyard surrounded by Dacheng Hall and Dacheng Gate was influenced by buildings and a dense plantation, and many wind shadows were formed. The wind velocity there was between 0.2 and 0.5 m/s, which is not conducive to effective ventilation.

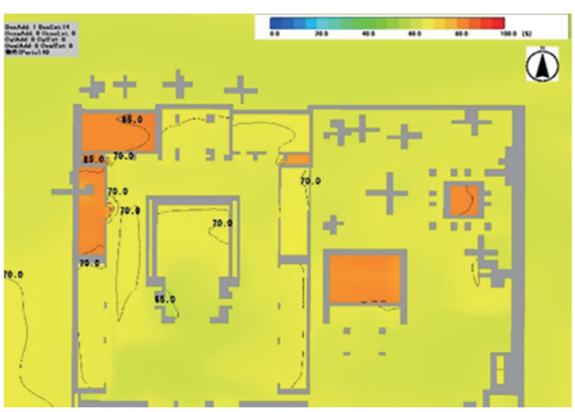

Fig 6. Indoor relative humidity field simulation
圖 6. 室內相對溼度場
Source: This stud

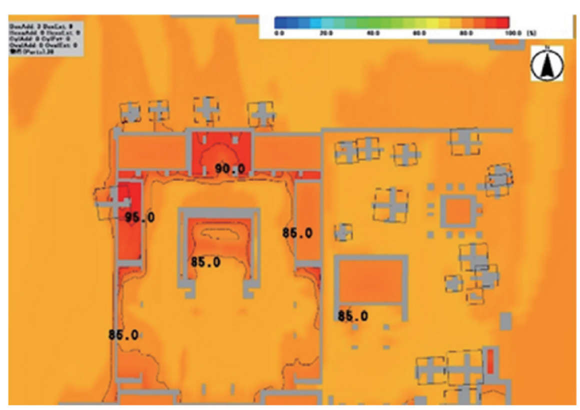

Fig 7. Indoor relative humidity field simulation
圖 7. 室內相對溼度場
Source: This study

The indoor space simulation results indicated that except for spaces such as the Storehouse of Books and Records, which was closed throughout the day, during this season, the Ritual Implements Storeroom has the highest relative humidity (Fig 8). Although the wind velocity at the east and west sides of Dacheng Hall increased, it only increased the indoor wind velocity of the East and West Wings to 0.3–0.5 m/s. The indoor wind velocity of the Ritual Implements Storeroom remained 0.02–0.1 m/s. Because the indoor area has almost no air movement, the Ritual Implements Storeroom should be dehumidified during that season or have increased ventilation to reduce the relative humidity.

4.4 The night time in cool season

The major wind direction was north-northeast. During the night, the windows of the Ritual Implements Storeroom, Musical Instrument Storeroom, and Yi Cheng School were all shut, and only the windows at Dacheng Hall and the East and West Wing were open. Indoor spatial simulation results revealed that the relative humidity of the Musical Instrument Storeroom at night during the cool season was higher than that of other spaces, ranging from 88–95% (Fig 9). Additionally, its indoor temperature was 20–23 °C, which is close to the dew point. For example, as a first approximation, at a temperature of 20 °C and relative humidity of 95% the dew point is 20 °C, meaning that water will condense on surfaces leading to biological growth and damage to the fabric of the building. Results of this study suggests that this place conduct night time dehumidification or open the doors and windows to maintain ventilation to reduce relative humidity.

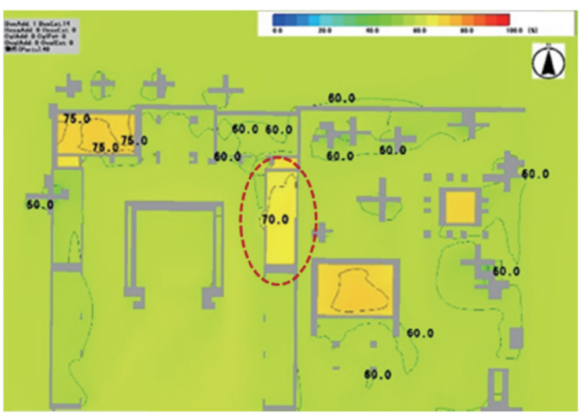

Fig 8. Ritual Implements Storeroom relative humidity distribution (marked by the red dashed-line circle)
圖 8. 禮器庫相對溼度分布圖（紅色虛線圈選位置）
Source: This study

5. CONCLUSIONS

This paper focuses on the micro-scale of climate change issues and examines the current environment as the basis for research in the future. Under the condition of not

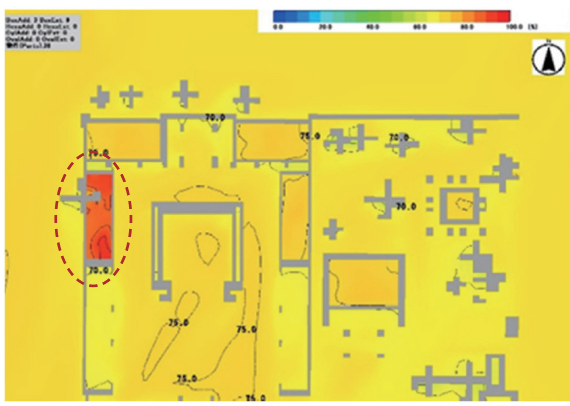

Fig 9. Indoor relative humidity field simulation (Musical Instrument Storeroom is marked with the red dashed-line circle)
圖 9. 室內相對溼度分布圖（樂器庫為紅色虛線圈選處）
Source: This study

changing the building materials or layout, the preventive conservation methods and mechanisms proposed in this paper are for implementation in daily management and maintenance, and the application of CFD simulation for physical treatment methods.

According to the simulation results, the Ritual Implements Storeroom and the Musical Instrument Storeroom were the main problem areas and indoor ventilation and dehumidification equipment need to be installed. The highest average relative humidity was determined indoors regarding the Musical Instrument Storeroom, where the crown of the mango behind it is about 4–6 m in diameter. The roof is shaded in the day time, so that sunlight is blocked, and the indoor moisture is reduced. Since the Musical Instrument Storeroom displays wooden exhibits, it is recommended to either change the area where these are displayed, or transplant or trim the rear mango trees to allow more sunlight to fall on the building; thus reducing indoor moisture. In addition, Dacheng Hall and Chong Sheng Shrine have a relative humidity of more than 80% during the hot season. It is recommended to actively dehumidify these spaces during the hot seasons. The space at the bottom of the front porch of Yi Cheng School and the Library of Books Collection also showed a relative humidity higher than 80% during the hot season. It is recommended to open the side door during the hot season to increase ventilation and thus reduce relative humidity.

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