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Spatial and temporal changes in microclimate affect disease distribution in two ancient tombs of Southern Tang Dynasty

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ABSTRACT

Two tombs of the Southern Tang Dynasty (Qinling Tomb and Shunling Tomb), the most important cultural heritages in China, were built for emperors 1000 years ago and decorated with murals and stone sculptures. After their excavation in the 1950s, it was found that drastic fluctuations in the environment within the tombs had caused multiple diseases, such as salt efflorescence, powdering, and biodeterioration, which led to irreversible damage to the murals. This research comprised long-term (yearly) environmental monitoring and short-term (monthly) investigation into the distribution of salt crystallization and microbial growth within the two tombs. The objective was to unveil the relationship between the temporal and spatial distributions of the mural diseases and environmental characteristics while proposing a promising environmental regulation strategy for relic conservation. The results showed a gradual reduction in temperature fluctuation from the entrance to the back chamber and a distinct vertical stratification in relative humidity. The relative humidity in the upper areas of the tombs reached 100% during summer, while it averaged around 40–50% in the lower areas during winter. Consequently, significant condensation was observed on the ceiling in summer, whereas salt crystallization occurred on the murals in the lower space in winter. The distribution of these diseases was influenced by the airflow exchange between the interior and exterior. Furthermore, the structural disparities between the two tombs contributed to higher relative humidity and greater microorganism coverage in the Shunling Tomb compared to the Qinling Tomb. From the abovementioned findings, we suggest that microclimate control is essential for mitigating mural deterioration and should be paid more attention in the future.

1. Introduction

Murals in tombs and caves are important cultural heritages that record civilizations and provide evidence for exploring the history of different eras and regions [1,2]. Deeply buried underground, tombs often exhibit unique environmental characteristics, such as stable temperature, high relative humidity, and a lack of ventilation and light inside the tombs, which is cut off from the exterior world before excavation [3–5]. After excavation, tombs undergo substantial environmental changes [6–9], such as drastic fluctuations in

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temperature and humidity. Microbial spores, brought in by the inflow of air from the outside and/or by visitors, are a major source of biodeterioration for tombs [10,11]. Following colonization, microbial community structures are influenced by soluble salts [12,13], light intensity [10,14], and moisture [15,16]. For example, an ambient relative humidity exceeding 75% greatly accelerates microbial growth [17]. When the air becomes saturated, condensation may occur on the wall surface [18], further promoting the risk of biological colonization [19–21]. The acids produced during microbial growth can corrode mural materials, leading to irreversible damage [22,23]. Furthermore, opening tombs exacerbates the humidity fluctuations in the chamber, as well as the cycles of salt crystallization/dissolution and hydration/dehydration [24], which are associated with repeated volume changes and confined mechanical stresses transferred to the material, ultimately leading to material loss and exfoliation [25–28]. In this respect, physical, chemical, and biological deterioration together poses significant threats to the historical, cultural, and artistic information of the tombs.

Salt weathering and biological deterioration are common diseases in tombs, and various direct and indirect treatments have been researched to minimize these diseases. Fungicides have been used to remove micro-organisms from cultural heritages in many cases, such as the Crypt of the Original Sin [29], the Lascaux Caves [22,23], and the Tomba degli Scudi [30]. The results showed that biocide treatments may be beneficial in solving immediate microbial problems, but it is difficult to understand the whole ecosystem and estimate the long-term impact of fungicides [31,32].

Environmental control is another strategy by which to mitigate condensation and biological growth as well as salt crystallization. In museum conservation, the preservation environment for different materials is specified, mainly because the objects are then detached from the soil and fully influenced by the characteristics of the surrounding environment. In the case of in situ wall paintings, the deterioration of the material is influenced by the properties of the material itself, the environment of the tomb, and the thermal and humid state of the surrounding soil, making it difficult to apply the museum's control standards to the environment within the tomb. In Altamira Cave, condensation and microbial metabolic activity at the entrance have been somewhat reduced by installing a two-layer gate and insulation system, but the effects of temperature, humidity, and carbon dioxide from visitors to the cave remain [33]. Three antechambers were built in the Takamatsu Tomb to maintain a stable environment in the tomb and to keep it preserved in good condition for the next 30 years. Although the tomb was subsequently disintegrated and placed in a museum for preservation due to mold growth in the tomb, environmental moderation can be considered an effective method for environmental control [34,35]. Benavente [36] suggested maintaining a relative humidity of lower than 60% to minimize all the rock decay processes in the Postumius Tomb in a semiarid climate. Due to the humid climate, however, the humidity inside the tomb of Baekje 6 was chronically around 95%; an air conditioning system was installed in 2003 to control the temperature at 18 °C and the relative humidity at 90% inside the tomb,

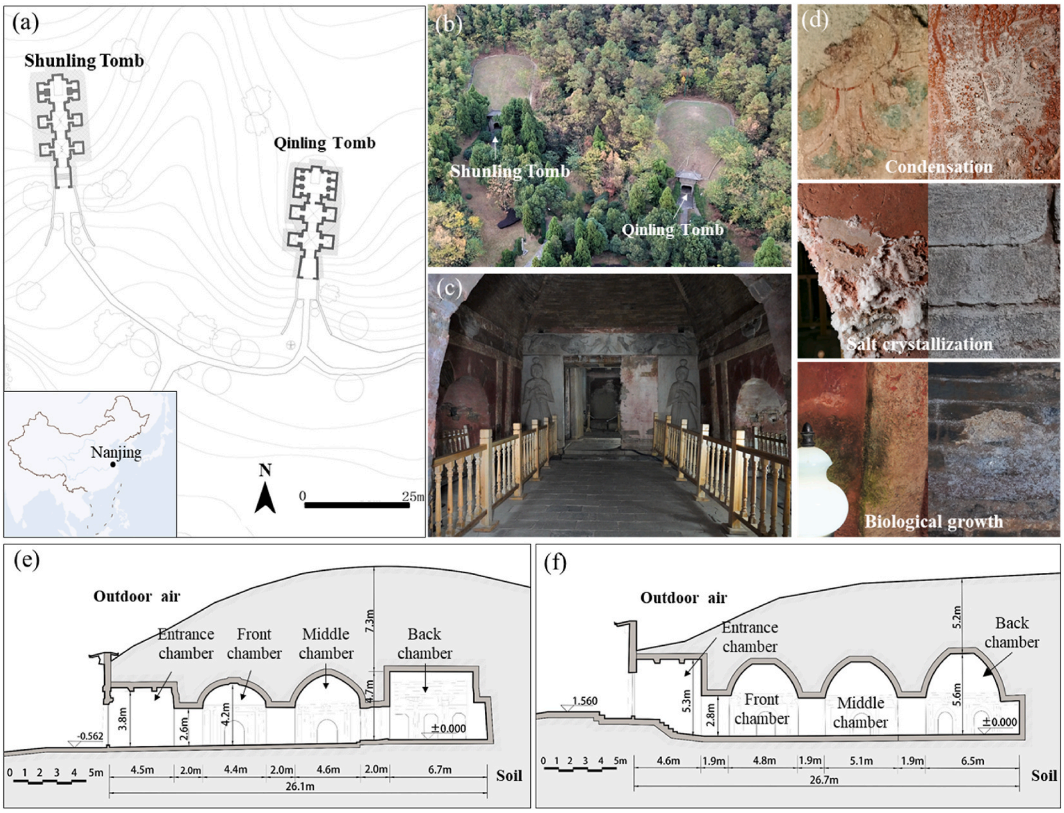

Fig. 1. Introduction of two tombs of the Southern Tang Dynasty: (a) location of the tombs; (b) view of the tombs; (b) stone sculptures in the Qinling Tomb; (d) the representative diseases, namely condensation, salt crystallization, and biological growth; (e) cross-section of the Qinling Tomb; (f) cross-section of the Shunling Tomb.

causing the cracking of the murals, and the system was shut down in 2011 [37]. The main diseases, their causes, and related environmental factors vary from site to site depending on the tomb structure and the outside environments [38]. Therefore, the scope for environmental regulation for tombs under in situ conservation needs to consider the effects of climatic conditions.

As mentioned above, relic deterioration is influenced by both the thermal and hygroscopic properties of the materials formed and the microclimate stored. The temperature and humidity in tombs are important factors and are greatly influenced by climatic conditions, locations, geology, and tomb structures. Thus, understanding the spatial and temporal changing patterns of temperature and humidity and their influences on biotic and abiotic diseases in cultural sites is a prerequisite for their conservation. To this end, taking the two tombs of the Southern Tang Dynasty as examples, multi-point environmental monitoring and regular disease surveys were conducted to clarify the adverse influences in the in-situ environment regarding the conservation of the tombs, and a potential environmental control strategy for the tombs is proposed.

2. Site and methods

2.1. Study object

Chinese tombs are mostly multi-chambered brick tombs with large chamber volumes [8,24,39,40]. Two tombs of the Southern Tang Dynasty (Qinling Tomb and Shunling Tomb), are significant cultural heritages in China. The tombs, built for two emperors of the Southern Tang Dynasty 1000 years ago, provide invaluable physical evidence for studying the imperial funeral system of that period. The two tombs are located approximately 50 m apart at the southern foot of the mountains and are enveloped by abundant vegetation (Fig. 1a and b). They represent sizable semi-underground structures comprising three main chambers decorated with murals and stone sculptures (Fig. 1c). While the back chamber of the Qinling Tomb was constructed using stone, the other chambers in the Qinling Tomb and the Shunling Tomb were made of blue brick, serving as a supporting structure for the murals (Fig. 1). The tombs are open to visitors from 8:00 to 17:00, and all the chambers of the Qinling Tomb (front, middle, and back) are illuminated, while the middle and back chambers of the Shunling Tomb are also illuminated. The tombs differ in terms of burial depth and the tomb structure (Fig. 1e and f): the entrance chamber of the Shunling Tomb includes downward steps of about 1.2 *m*, while the floor in the Qinling Tomb gradually ascends from the entrance to the back chamber, which sits approximately 0.5 *m* higher than the ground level outside. The soil stratigraphy within a range of 0–20 *m* depth around the tombs can be classified as follows: topsoil (weakly permeable layer; burial depth: 0∼1.0 *m*), loose fill soil (weakly permeable layer; burial depth:8.5–8.5 *m*), silty clay (slightly permeable layer; burial depth:0.6–9.0 *m*), slope deposits (susceptible to softening and increased permeability after water immersion; burial depth: 2.1–16.5 *m*), highly weathered diorite (rock fragmentation, high permeability; burial depth: 5.5–16.5 *m*), and moderately weathered diorite (rock fragmentation, high permeability). In addition, it was reported that there is no groundwater at a depth of 20 *m*. Therefore, the primary factor influencing the tombs is surface water.

Nanjing, located in the southeast of China, experiences hot summers and cold winters. Fig. 2 shows the weather data measured from November 2020 to October 2021 in the vicinity of the two tombs of the Southern Tang Dynasty. The temperature ranged from −11.0 °C to 38.0 °C, with an average of 17.1 °C, while the relative humidity ranged from 24.1% to 100.0%, with an average of 81% (Fig. 2a). The annual total solar radiation was 1110.7 kW h/m^2 (Fig. 2b). Additionally, the average annual rainfall was 940.4 mm, with the majority occurring during the summer months (Fig. 2c).

2.2. Methods

2.2.1. Environment monitoring

The monitoring plan is shown in Fig. 3a and b. Both tombs are characterized by a single opening (entrance), considerable depths, and significant heights, which may result in temperature and humidity gradients in both horizontal and vertical directions. In this study, temperature and humidity were recorded at a height of 3.0 *m* in three chambers (front, middle, and back), at a height of 0.1 *m* in

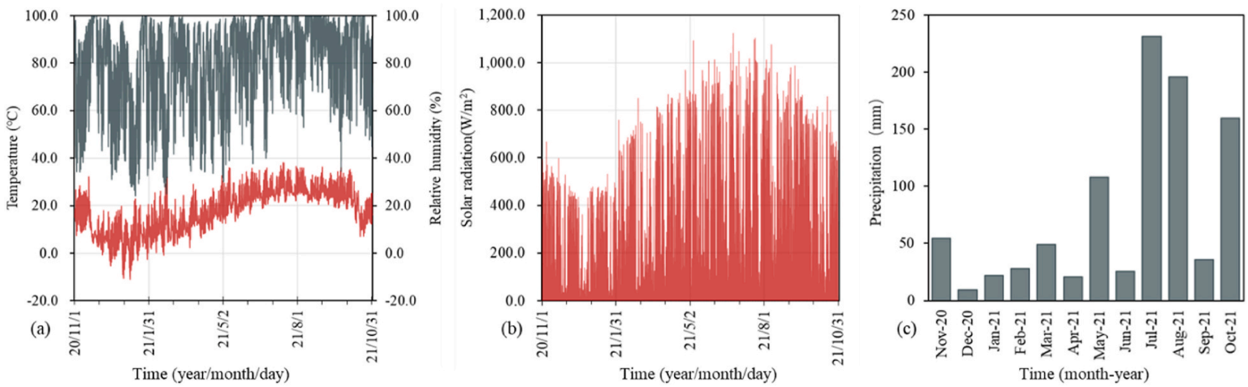

Fig. 2. The weather data: (a) temperature (°C) and relative humidity (%); (b) solar radiation (W/m^2); (c) monthly precipitation (mm).

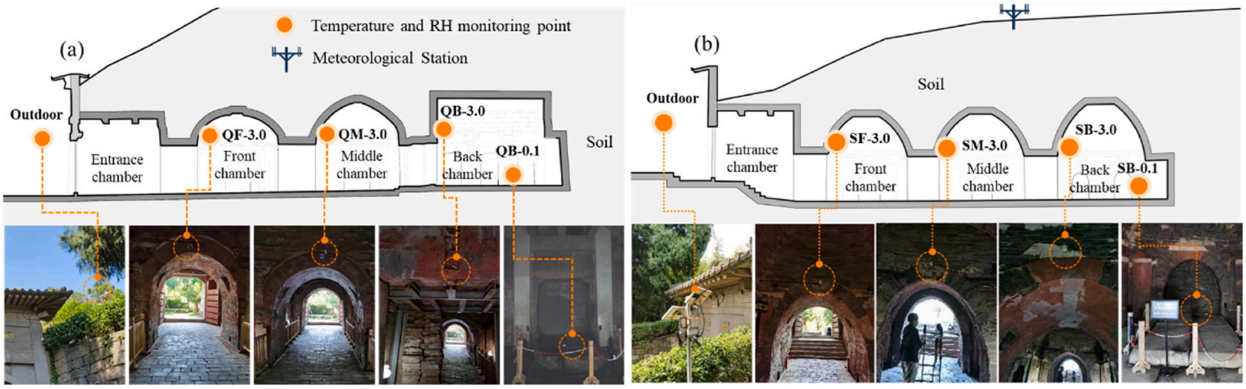

Fig. 3. The monitoring plan for the two tombs of the Southern Tang Dynasty: (a) Qinling Tomb; (b) Shunling Tomb. The monitoring point is indicated by the chamber name and the monitoring height, such as "QF-3.0".

the back chamber of both tombs and approximately 5 m above the ground outside the tombs. Air temperature and humidity were measured using electronic recorders (HOBO MX2301, USA) with a precision of ±0.2 °C and ±2.5%, respectively, and a measurement range of −40 °C–70 °C and 0%–100%, respectively. Additionally, a weather station (HOBO U30, USA) was installed on top of the Shunling Tomb. The monitoring was conducted at 30-min intervals from October 2020 to October 2021. Furthermore, the air temperature and relative humidity were recorded at a height of 0.1 m in the front chambers of both tombs from September 18th, 2021 to October 31st, 2021.

2.2.2. Field investigation

Salt crystallization and microbial growth can lead to discoloration, chalking, and flaking of the murals, posing a threat to their preservation (Fig. 1d). The processes of salt crystallization and microbial growth are closely associated with moisture, and condensation serves as an indicator of water saturation in the murals. Therefore, this study mainly investigated the trends in salt crystallization, condensation, and microbial growth coverage area within the tombs under changing microclimate conditions.

The disease distribution within the tombs was investigated monthly throughout 2021. Initially, a 3D scanner was used to model the tombs (Fig. 4), and CAD software was employed to depict the east and west walls. Subsequently, the disease distribution on the east and west walls was investigated, photographed, recorded, and mapped using CAD software monthly in 2021. Data from four months (winter: Jan. 2021; spring: Apr. 2021; summer: Jul. 2021; autumn: Oct. 2021) were selected for analysis.

The area covered by salt crystallization, condensation, and micro-organisms was examined through visual identification and photographic comparison. Salt crystallization appeared in needle-like and powdery forms, condensation manifested as visible surface water droplets or dampness, and micro-organisms presented as brown and white dotted areas. Due to the changing coverage area of these phenomena over time and the subjective nature of visual identification, there may be errors in the reported coverage compared to the actual situation. However, this investigation focused on the temporal trends in the coverage area of salt crystallization, condensation, and microbial growth. In order to establish their relationship with environmental characteristics, the results obtained through visual observation are considered acceptable in this research.

Additionally, measurements of wall surface temperature and air velocity were conducted in the tombs. The surface temperature was measured using an infrared thermometer (Fluke; measurement range: −40 °C–55 °C; precision: ±1 °C), while air velocity was measured using an anemometer (Testo 405i; measurement range: 0 m/s to 30 m/s; precision: ±0.2 m/s).

Fig. 4. The three-dimensional scan of the west wall of the Shunling Tomb in January 2021.

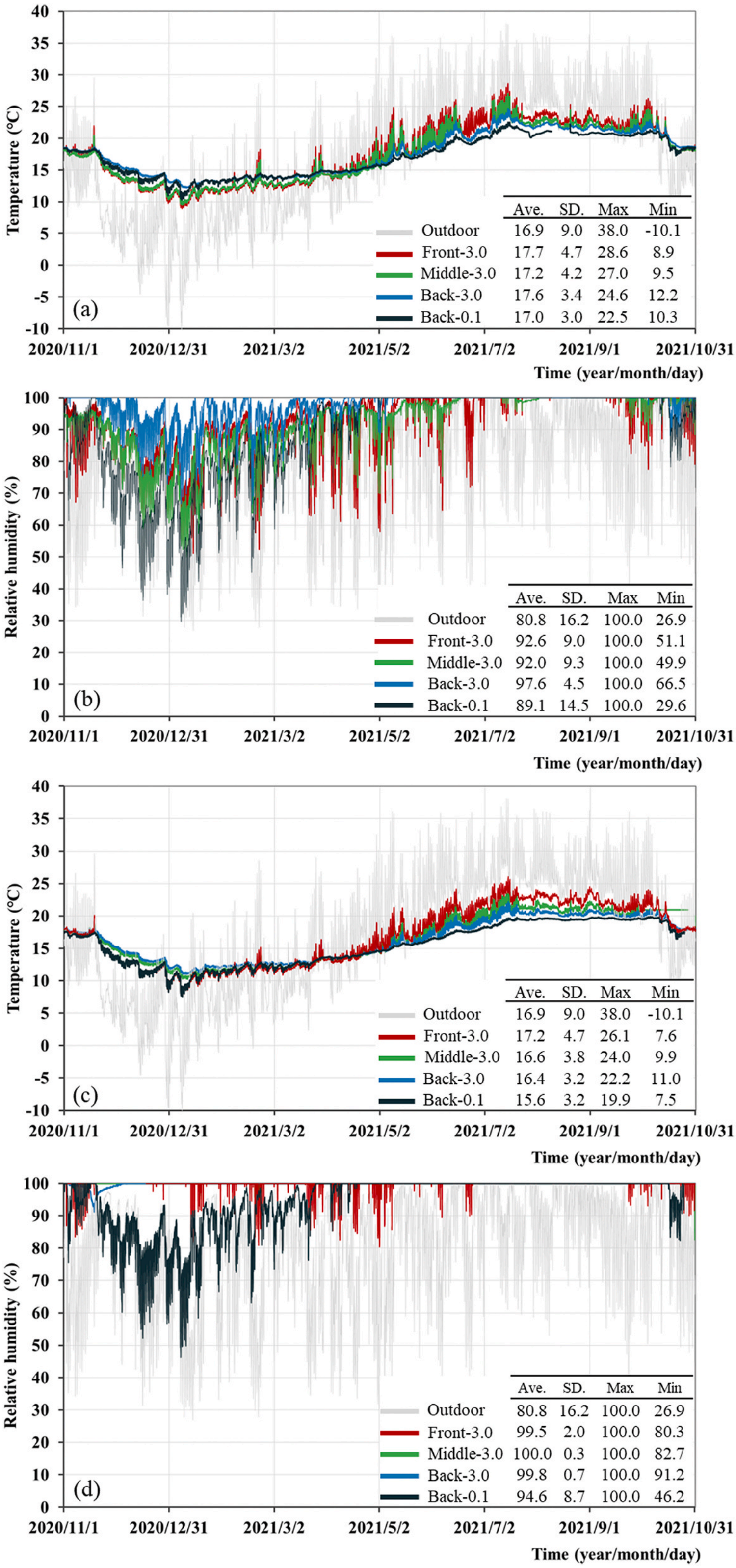

Fig. 5. Measured temperature (a) and RH (b) in the Qinling Tomb; measured temperature (c) and RH (d) in the Shunling Tomb (Nov. 2020~Oct. 2021).

3. Results

3.1. Microclimate measurement

The measured air temperature and humidity in the two tombs from November 2020 to October 2021 are shown in Fig. 5. The temperature and humidity fluctuations in both tombs changed with the climate. Compared to the outdoor temperature, it was warmer in winter and cooler in summer within the tombs. In Qinling Tomb, the average temperature difference among the monitoring points was less than 1 °C annually. The temperature fluctuation range gradually decreased from the front chamber to the back chamber, with the following order: outdoor (48.1 °C) > QF-3.0 (19.7 °C) > QM-3.0 (17.5 °C) > QB-3.0 (12.4 °C) > QB-0.1 (12.2 °C). The daily amplitude of temperature fluctuation in QF-3.0 was up to 6.3 °C during summer (Fig. 5a). In the Shunling Tomb, the average annual temperature decreased from the front chamber to the back chamber, with the temperature at SF-3.0 being approximately 1.6 °C higher than that at SB-0.1. The annual temperature fluctuations decreased from the outdoors to the back chamber: outdoor (48.1 °C) > SF-3.0 (18.5 °C) > SM-3.0 (14.1 °C) > SB-0.1 (12.4 °C) > SB-3.0 (11.2 °C) (Fig. 5c). Importantly, there was no significant delay in the occurrence of temperature peaks between the tombs and the outdoors, indicating a strong influence of the external environment on the interior temperature.

Furthermore, in both tombs, the temperature at the height of 3.0 *m* was higher than that at the height of 0.1 *m* for over 80% of the monitoring period (Fig. 6b), with a temperature difference of approximately 1 ± 1 °C more than 50% of the time. Regarding seasonal variation, the vertical temperature difference was more pronounced in winter and summer, while it was smaller in spring and autumn (Fig. 6a).

The relative humidity in tombs, which is influenced by both the moisture content of the air and the temperature, showed a different trend compared to temperature. Compared with the outdoor conditions, the relative humidity was significantly higher in the tombs. In the Qinling Tomb, the largest annual fluctuation occurred at QB-0.1 (29.6%–100%), with the largest daily amplitude of 32% (29.7%–62.3%) in January. Conversely, the smallest annual fluctuation was observed at QB-3.0 (66.5%–100%), with an average daily relative humidity exceeding 99% for 227 days (Fig. 5b). In the Shunling Tomb, the largest annual fluctuation occurred at SB-0.1 (46.2%–100%), while the smallest occurred at SB-3.0 (80.3%–100%), with a daily average relative humidity exceeding 99% for 349 days (Fig. 5d). Both tombs presented clear vertical stratification in relative humidity, with the relative humidity at height 3.0 *m* higher than that at 0.1 *m* for over 85% of the monitoring period. The difference in relative humidity was approximately 2 ± 2% for over 50% of the time (Fig. 5d). Seasonally, the vertical humidity difference within the tombs was most significant in winter (December to February), with a maximum difference of 50% (Fig. 6c). However, the difference gradually decreased thereafter, with the humidity in the chambers reaching nearly 100% from May to September (Fig. 6c).

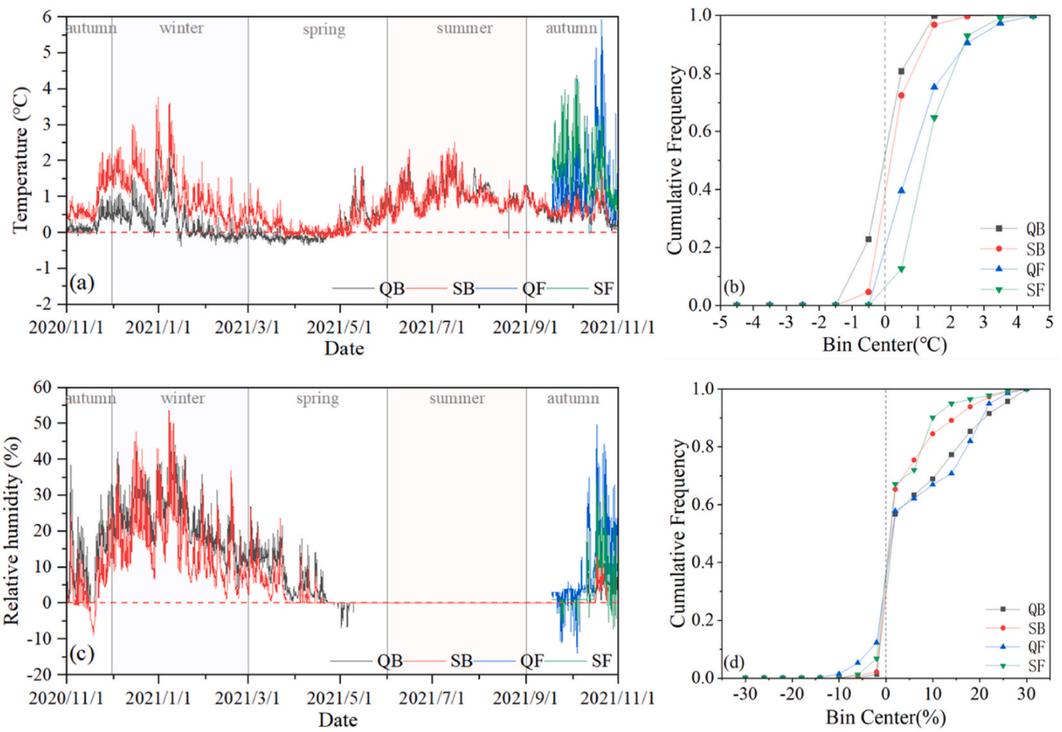

Fig. 6. Fluctuations and cumulative frequency in vertical temperature differences (ãb) and relative humidity (c ~ d) in the front and back chambers. The temperature differences ranged from −5 to 5 °C in 10 intervals (1 °C per interval) and the humidity differences ranged from −32% to 32% in 16 intervals (4% per interval). (the vertical difference = h3.0-h0.1).

The findings indicate the presence of horizontal and vertical temperature and humidity gradients in the tombs. Notably, compared to the same location in the Qinling Tomb, the Shunling Tomb experienced lower temperature and higher relative humidity throughout the year.

3.2. Field investigation

The spatial distribution of salt crystallization, condensation, and microorganism growth within the tombs was investigated.

The analysis of the salt crystallization sample taken from the tombs revealed that it mainly consisted of sodium and calcium sulfate. These salts are highly destructive and can cause damage to murals. In the Qinling Tomb, salt crystallization coverage was highest in winter, followed by spring, autumn, and summer (Fig. 8a). It is noteworthy that the relative humidity within the chambers reached its lowest point during winter (Fig. 5b). In January 2021, salt crystallization mainly occurred on the lower part of the walls in the front and middle chambers of the Qinling Tomb (Fig. 7a). Additionally, salt crystallization was observed on the upper walls of the front chamber. There are two main reasons: firstly, there was a significant amount of condensation on the upper wall in the front chamber during summer (Fig. 7c), indicated by high water content in that area; secondly, the relative humidity at Front-3.0 and Back-0.1 during winter reached a minimum of 30% and 50%, respectively (Fig. 5b), posing a high risk of salt crystallization. In the Shunling Tomb, the most significant salt crystallization was observed in January, covering an area of up to 6%. As a substantial amount of salt in the tomb had formed a solid crust, the variation in coverage throughout the year was less pronounced. Salt crystallization was observed in lower areas of the walls in the entrance, the front, and the middle chambers (Fig. 7e). Furthermore, the velocity and direction of airflow were measured in January (Fig. 7e). Due to the temperature difference between the interior and the outside, cold (and dry) outdoor air flowed into the tomb through the lower space, while the hot (and humid) indoor air flowed out through the upper space. This led to a decrease in relative humidity in the lower space, resulting in an increase in the evaporation rate from the walls and the occurrence of salt crystallization.

Condensation is identified as one of the sources of moisture within the tomb. The investigation revealed that condensation mainly occurred in both tombs in summer (Fig. 8b), with relative humidity remaining at 100% during this period (Fig. 5b and d). In the Qinling Tomb, the condensation was primarily found on the ceiling of the entrance and front chambers, as well as on the stone surfaces of the back chamber (Fig. 7c). Condensation began appearing on the stone floor as well as the stone walls of the back chamber in May, with the maximum coverage from July to August. In the Shunling Tomb, there was less condensation, which occurred on the ceiling of the entrance chamber, the corridor ceiling, and the stone floor of the back chamber (Fig. 7g). The condensation occurred mainly in summer, covering approximately 30% of the walls in the Qinling Tomb and 3% in the Shunling Tomb.

Fig. 9a and b shows the measured surface temperature and air velocity in both tombs in July. The dew point temperature of the

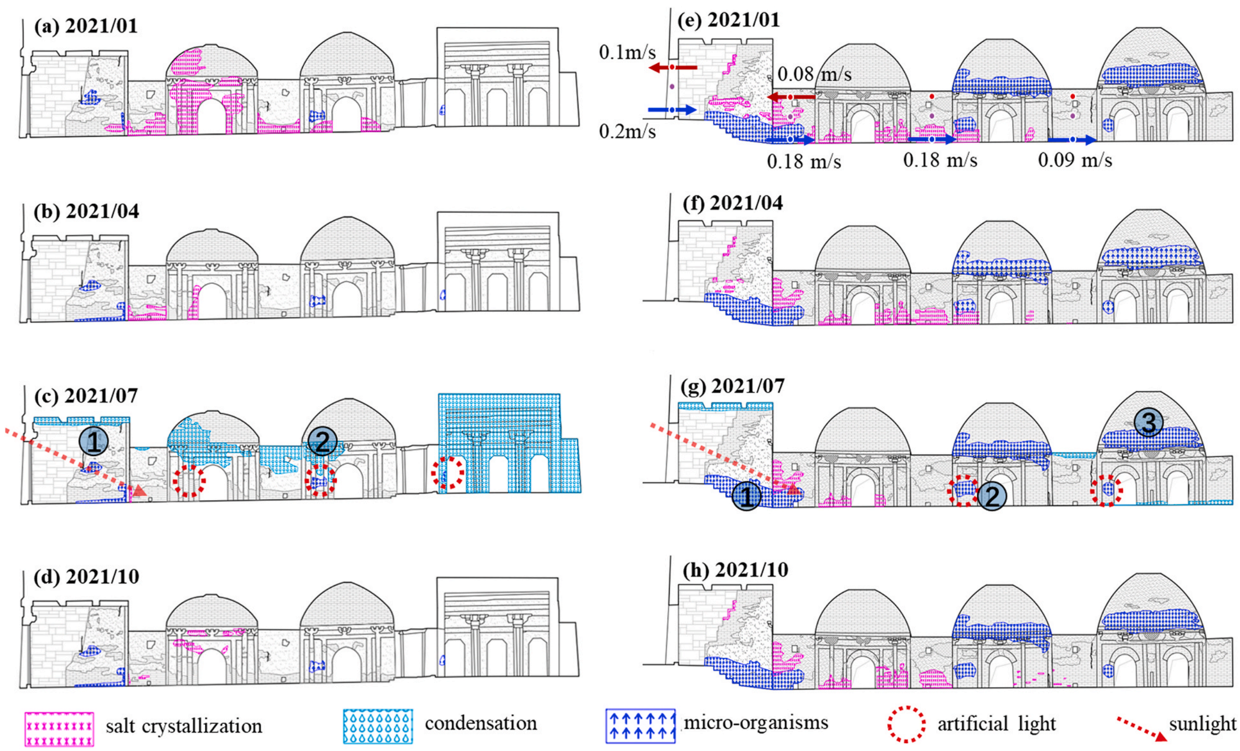

Fig. 7. Distribution of salt crystallization, condensation, and biological growth in (a–d) the Qinling Tomb and (e–h) the Shunling Tomb during four seasons. The symbols ①, ②, and ③ indicate the 3 main areas of microbial distribution.

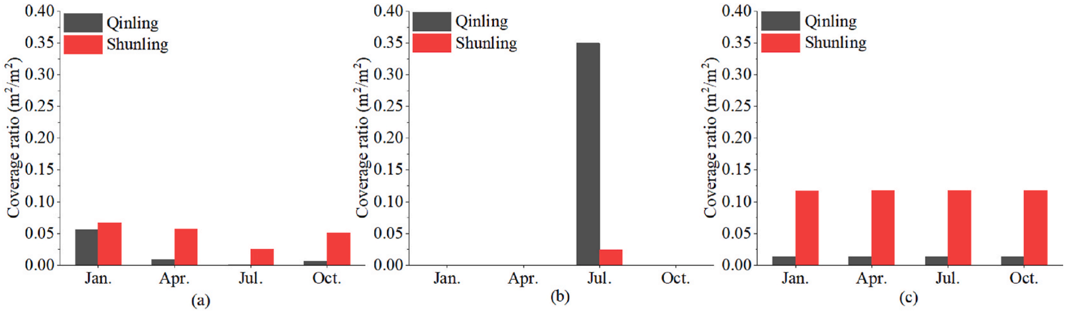

Fig. 8. The coverage ratio of (a) salt crystallization, (b) condensation, and (c) micro-organisms during four seasons.

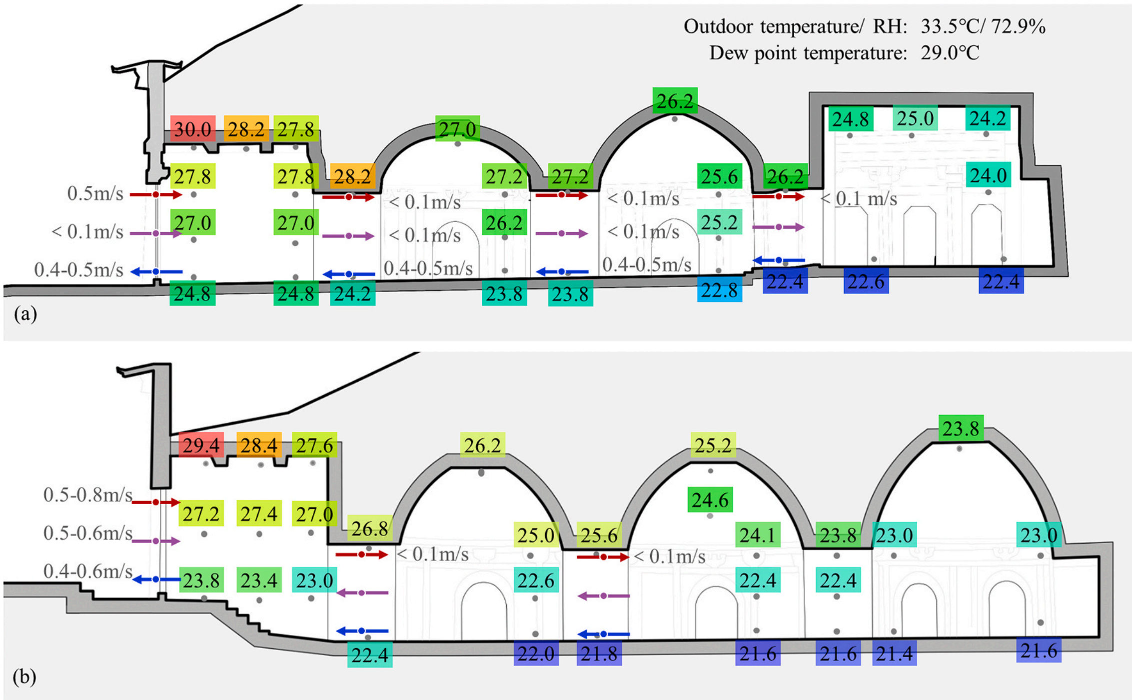

Fig. 9. Measured surface temperature of the walls and air velocity in (a) the Qinling Tomb and (b) the Shunling Tomb at 15:30 on July 11, 2021.

outdoor air was higher than that of most interior surfaces. Consequently, the temperature difference between the interior and exterior caused the outdoor air to enter the tomb through the upper space. As the external air flowed into contact with the cold interior walls, condensation occurred on the upper surfaces of the tombs. This suggests that the amount of air exchange between the interior and exterior during summer should be reduced to mitigate condensation within the chambers. Additionally, it was observed that the airflow velocity in the Shunling Tomb was lower than that in the Qinling Tomb.

Regarding biological growth in both tombs, micro-organisms were mainly distributed in three areas within each tomb (Fig. 7c and g, ①②③). The first area was the lower part of the walls in the entrance chamber, which was exposed to sunlight and covered with greenish-brown micro-organisms. The second area was the walls exposed to the artificial light in both tombs. The growth of phototrophic micro-organisms in these two areas was mainly influenced by illumination (natural and artificial lights). Moreover, extensive mold growth was observed on the upper walls in the middle and back chambers of the Shunling Tomb (the third area). This region had a stable microclimate with relative humidity exceeding 95% throughout the year, creating favorable conditions for mold growth. The micro-organisms did not vary significantly in one year (Fig. 8c), while showed a gradual increase over the years, indicating that the environment within the chambers was conducive to their growth (Fig. 10a–c).

Fig. 10. Microbial growth in two tombs from 2021 to 2022: (a) the west wall in the entrance chamber of the Shunling Tomb; (b) the east wall in the middle chamber of the Qinling Tomb; (c) the west wall in the middle chamber of the Shunling Tomb.

4. Discussion

4.1. Relationship between chamber environment and disease distribution

Underground and semi-underground sites, including tombs, often face common challenges such as salt weathering and biological growth. As tombs are typically surrounded by soil with only one outlet to the outside, the microclimate within tombs is influenced by two main factors: air exchange at the entrance and heat and moisture transfer through the surrounding soil.

The two tombs of the Southern Tang Dynasty are open for display during the daytime, and the air exchange at the openings significantly affects the hygrothermal conditions within the tombs. The measurements show temperature and humidity gradients from the entrance to the back chamber. Additionally, there was a vertical hygrothermal gradient in the tombs with the lower space being cooler and dryer than the upper space. This phenomenon is more common in tall spaces [41]. Varas Muriel et al. found that in a 5 *m* high heated church, the air temperature near the ceiling was 4 °C and 3 °C higher than the floor temperature [42]. In winter, the temperature difference between the interior and exterior of the tomb caused airflow, resulting in low humidity and salt crystallization in the lower space of the tombs. The hot (and humid) indoor air flows out through the upper space and the cold (and dry) outdoor air flows into the tomb through the lower space. However, the drying effect on the interior air gradually decreased from the entrance to the back chamber, maintaining a high relative humidity with minimal risk of salt crystallization in the back chamber. Germinario et al. observed that near the entrance of an underground archaeological-historical site, the wider fluctuations of air temperature and humidity created conditions for salt crystallization in the dry winter and deliquescence in summer, with the relative humidity in the innermost underground areas reaching nearly 100% and being mostly salt-free [25]. Crystallization-deliquescence cycles occur due to small variations in temperature and humidity. Mirabilite and epsomite undergo phase changes from crystallization to deliquescence and vice versa at approximately 83% relative humidity (temperature: 15–20 °C) [43]. Therefore, when the ambient relative humidity fluctuates above and below this range, as measured between November and May (Fig. 5) in the front chamber (F3.0) and the back chamber (B0.1), a crystallization-deliquescence cycle becomes possible. These findings indicate the influence of relative humidity fluctuations on the occurrence of salt crystallization in the tomb.

Salt migration, and crystallization-dissolution cycles rely on the presence of moisture. Within the tomb, condensation serves as a significant moisture source for murals. In summer, the condensation was mainly found on the upper surfaces and the stone walls of the back chamber in both tombs, facilitated by the influx of hot and humid outdoor air through the upper space. This condensation pattern corresponded to the seasonal trend of rainfall, which occurred mainly in summer. In the Postumius Tomb, salt weathering and condensation were most prevalent during the frequent rainfall in spring and autumn [36].

The investigation revealed significant microbial growth on the walls exposed to sunlight and artificial lighting within the tombs. However, in the Qinling tomb, under the same artificial lighting conditions, the microbial community thrived abundantly in the middle chamber while being scarce on the walls of the front chamber (Fig. 7c). Several factors may influence this phenomenon: the high humidity in the middle chamber might promote microbial growth, while the front chamber, being drier and colder during winter, may act as an inhibitory environment for microbial growth. Furthermore, through sequencing and analysis of bacterial communities in different chambers of the Qinling tomb, Li et al. discovered a significantly higher functional abundance of bacterial communities in the middle chamber compared to other positions in the tomb, posing a greater threat to the murals [44].

4.2. The effect of structural differences between the two tombs

The variability of temperature and humidity within tombs depends on various factors, including climatic conditions, tomb structure, burial depth, and tomb closure. For example, in an arid area, the main chamber of Tutankhamen tomb is approximately 15 *m* from the entrance, with steadily high temperature (22–28 °C) and a wide range of relative humidity fluctuates (15%–70%) [45]. In contrast, the Royal Tombs at Neungsan-ri, South Korea, located in a humid area and tightly sealed, presented relatively stable annual temperature (13–18 °C) and high humidity (98.5%–100%) in the main chamber, which is 5 *m* below ground. As a result, significant condensation occurred in the chamber [46]. Additionally, the presence of a dromos (a long entrance passage) in tombs appears to have a positive effect on stabilizing microclimatic conditions. In southern Spain, the Postumius Tomb, which has direct contact with the outdoors, experienced greater temperature and humidity fluctuations and more severe salt weathering in the tomb compared to the Circular Mausoleum, where the chamber is connected to the outside through a long tomb passage [36].

There were notable differences in environmental characteristics and disease distribution between the Qinling Tomb and the Shunling Tomb. In comparison to the Qinling Tomb, the relative humidity in the Shunling Tomb was significantly higher and more stable, resulting in extensive microbial growth within the tomb (Fig. 8). Both tombs consist of three chambers connected by 2.6 *m* high corridors, with the chambers reaching approximately 5 *m* in height, which formed the semi-close upper space in each chamber. Moreover, the indoor floor of the Shunling Tomb is approximately 1.8 *m* lower than the exterior, while the indoor floor of the Qinling Tomb is about 0.5 *m* higher than the outdoor ground. The discrepancy in ground and floor heights at the entrance of the Shunling Tomb impeded air exchange between the interior and exterior, resulting in prolonged high humidity and significant mold growth on the upper surface of the Shunling Tomb. The reduction in air exchange during summer is also a contributing factor to the relatively lower amount of condensation within the Shunling tomb. Another factor might be the composition of the tomb walls, with fewer stone walls and more exposed hygroscopic green bricks within the Shunling tomb. Generally, bricks have lower porosity compared to stone [47, 48]. Therefore, most of the moisture in the Shunling Tomb was absorbed by the blue bricks, resulting in less condensation.

4.3. Conservation measures

Since the distribution of salt crystallization and condensation in the tombs varied seasonally according to the outdoor climate, conservation strategies should be adjusted accordingly. In summer, condensation occurs due to the infiltration of hot and humid outdoor air into the tomb. To minimize moisture ingress, the amount of air entering the tomb can be reduced, or dehumidified measures can be employed. The former strategy can be implemented by reducing the opening hours, such as installing automatic doors at the tomb entrance, while the latter can be achieved through the use of air conditioners and dehumidifiers at the entrance. In winter, dryness and salt crystallization within the tomb can be mitigated by limiting the opening hours of the doors. For instance, automatic induction doors can be installed to keep the doors closed in the absence of visitors.

Micro-organisms growth is influenced by various factors, including nutrient resources, temperature, humidity, light, and interactions within the microbial community [49–51]. In both tombs, the growth of phototrophic micro-organisms can be inhibited by providing shade at the entrance to reduce light exposure or by reducing the duration of lighting using sound-controlled switches (where lights are activated only when visitor activity is detected). Additionally, Zhou et al. found that different light sources had varying effects on the composition of microbial communities in the Shunling tomb, with red light demonstrating a better inhibitory effect on fungi and actinobacteria [51]. This suggests that incorporating more red wavelength light sources in the tombs can be beneficial. The duration of favorable conditions for mold growth is also a determining factor [52]. Johansson et al. found that alternating the temperature weekly between 22 °C and 5 °C, or the relative humidity between 90% and 60%, resulted in lower mold growth rates compared to constant conditions of 22 °C temperature and 90% relative humidity, respectively [53]. Therefore, intermittent cooling or dehumidification. Methods can be employed to control micro-organisms. However, the influence of environmental factors on microbial community structure is complex and requires further investigation.

The effectiveness of environmental control strategies based on disease surveys and environmental monitoring analyses, will be predicted through numerical simulation and evaluated through on-site experiments in future studies.

5. Conclusion

Based on environmental monitoring and the distribution investigation, we analyzed the formation processes of salt crystallization, condensation, and biological growth in two open tombs with small antechambers. As a result, a potential and promising conservation strategy is proposed.

Our findings revealed the significant influence of outdoor climate on temperature and humidity fluctuations, as well as disease distribution within the tombs. The airflow resulting from temperature differences between the interior and exterior of the tombs during different seasons emerged as the main factor causing microclimate fluctuations within the tombs. During summer, hot and humid air entered into the tombs through the upper space, resulting in condensation on the ceiling of both tombs. Conversely, during winter, cold and dry air flowed inwards through the lower space of the tombs, leading to salt crystallization in the lower sections of the chambers. Furthermore, the high humidity and light conditions were found to promote microbial growth.

The pairwise comparison between the Qinling Tomb and Shunling Tomb indicated the differences in microclimate and disease distributions, which can be attributed to variations in the ground and entrance floor heights. These differences directly affect influencing the efficiency of airflow exchange between the interior and exterior of the tombs.

To mitigate temperature and humidity fluctuations as well as condensation and salt crystallization in the tombs, conservation measures are proposed such as reducing the airflow exchange between the interior and exterior of the tombs and regulating the temperature and humidity entering the tombs. When addressing the removal of micro-organisms from the tombs, it is crucial to consider controlling the micro-climatic conditions, such as the patterns of hygrothermal changes.

Author contribution statement

Changchang Xia: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.
Diandian Liu: Performed the experiments; Contributed reagents, materials, analysis tools or data.
Zhenyi Kong: Performed the experiments.
Huarong Xie: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.
Baogang Mu: Contributed reagents, materials, analysis tools or data.
Shuichi Hokoi: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.
Yonghui Li: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data included in article/supp. Material/referenced in article.

Declaration of competing interest

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

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